12-6-56

James G. Gaume, M.D.

PROCEEDINGS of the AMERICAN ASTRONAUTICAL SOCIETY

DEDICATED TO PROGRESS IN THE ASTRONAUTICAL SCIENCES

- I Space Flight Mechanics
- II Satellite Applications and Research
- III Space Medicine
- IV Relativity and Gravitational Research

3rd ANNUAL MEETING DECEMBER 6 - 7, 1956 NEW YORK, N.Y.

PLANTS AS A MEANS OF BALANCING A CLOSED ECOLOGICAL SYSTEM*

by

James G. Gaume**

Abstract:

A discussion of the theoretical possibilities of the use of green algae in effecting a symbiotic relationship between man and plant in closed systems such as a manned satellite or spaceship cabin.

\- - - - -

The earth, with regard to all forms of life, is a wonderfully balanced ecological system. Contained on it and in its atmosphere are all the elements necessary to sustain life in the various forms present in the system. We are not fully aware as yet of the part which each known element plays in maintaining the balance between plant and animal life. We do know, for instance, that the waste products of animal metabolism contain elements which are necessary for flourishing growth of plant life, and vice versa.

When the normal balance of the Earth's system becomes upset, either through some natural phenomenon or as a result of some activity of man, inadvertent or considered, nature has a way of restoring the balance by means of some very unusual occurrence. Thus, the eruption of a volcano replenishes the carbon dioxide in the air, and in addition, showers the surrounding land and water with lava and volcanic ash which contain the common and trace minerals which we know now to be necessary for good plant growth.

We know, too, that the relationship between plants and animals is not entirely symbiotic, but that in many instances it is dog eat dog - small animals are devoured by larger ones, which in turn are consumed by still larger animals. The same is true of the fish in the sea. On both land and sea are plants which devour insects, fish and small animals[15], which

* Presented at the Third Annual Meeting of the American Astronautical Society, 7 December 1956, New York, N.Y.

** Dept. of Space Medicine, School of Aviation Medicine, USAF, Randolph Air Force Base, Texas.

are caught in their clutches.

The basic source of food for the animal is the green plant. The plant takes light from the sun, carbon dioxide from the air, nitrogen, water and other elements in various forms from the soil, and synthesizes them into carbohydrates, proteins, and fats. The plant then serves as food for the animal organism, which ingests the plant in its natural form, breaks it all down and puts the parts back together again in a form which is acceptable to that organism. What is left after the animal metabolic processes have been completed, is returned to the soil, in the form of organic semi-solid waste, or to the air as gaseous carbon dioxide. Water, of course, in various amounts, accompanies all forms of waste excretion. Food comes to humans directly as plant products, or indirectly, first having been changed into an animal food source.

The return of animal waste to the soil, and the decomposition of dead plant structures, replenishes the necessary growth factors removed from the soil by growing plants. The Chinese rice farmer has known this for several millennia and utilizes all excreta as fertilizer for his rice crop. His method of doing so, however, is objectionable to us, esthetically, and is fraught with the dangers of transmitting disease. We, therefore, have developed methods of changing waste matter into the acceptable form of commercial fertilizer. The same is being done with food waste, by means of digestive bacterial action, to produce another form of fertilizing compound.

The point is, that all forms of natural waste can be utilized to enrich the soil and promote growth of essential plant foods, thus completing the cycle in the transformation of energy as it is used to sustain and make flourish the growth of living organisms.

Man, animals and plants require oxygen for cellular respiration of food substances. As a part of their metabolic processes, plants require and take up carbon dioxide from the air. During the photosynthetic phase of metabolism plants produce oxygen in excess of their needs. In the dark phase, exogenous oxygen must be available. Under proper conditions, however, a net oxygen gain can be accomplished over a cycle of light and dark phases. Man and animal can respire the oxygen, producing carbon dioxide which is utilized by plants. Thus we are furnished with another example of the mutually beneficial existence which occurs between animal and plant.

So much for the general consideration of the earth as a balanced ecological system. Let us proceed to the main point of discussion - the use of plants as a means of balancing a small closed ecological system. In establishing this balance, three objectives must be accomplished:

1. to provide a means of gas exchange between human

and plant growth,

2. to provide a source of food by harvesting the excess plant growth,

3. to provide a means of disposal of the liquid and solid waste from the human.

Conceivably, a miniature sealed system, comparable to the earth could be set up, which could maintain human occupants in good health - provided a suitable plant organism, or organisms, could be found capable of fulfilling these three objectives.

It is now apparent that such an organism is one which until recently, has been considered a useless and undesirable one - one of the lowliest of plants - the simple green alga.

Let us consider now the use of algae, as a means of attaining the three goals outlined, and discuss the characteristics which would enable us to use such micro-organisms in a closed system.

1. Gas Exchange - Green algae, such as Chlorella, are particularly suitable as a photosynthetic gas exchanger. They are single-celled, small, round bodies about the size of a red blood cell. Since they have no specialized organs, as do higher plants, the photosynthetic process can be fully utilized in oxygen evolution and in growth, manifested by production of new cells. This activity can continue endlessly, in algae, without the presence of a dark phase, if light and nutrients are plentiful.

The potential oxygen production of such algae is extremely good. Studies in this area are now being made by Dr. Jack Myers, at the University of Texas, under an Air Force contract with the School of Aviation Medicine. Dr. Myers has found that five pounds, fresh weight, of the common alga Chlorella pyrenoidosa under optimal conditions, is sufficient to support one man with regard to gas exchange.[9] This means that five pounds of the algae can produce enough oxygen to meet the needs of one man, and can absorb the carbon dioxide produced by one man, during a given period of time. Thus, one human and five pounds of this alga, under suitable conditions could live symbiotically in a sealed cabin with regard to oxygen and carbon dioxide exchange.

Chlorella pyrenoidosa, in short-term experiments, attains maximum growth rate at low light intensities, whereas maximum oxygen evolution occurs at considerably higher illumination, in experiments of the same length.[10] In long-term experiments, the growth rate and oxygen production curves become almost the same. This is excellent for our purpose, as we shall see later.

In continuous growth experiments of longer duration, the optimum light intensity for these two factors is 500 foot candles of light. By comparison, the incident sunlight available at the earth's surface is 10,000 f.c. of light, or slightly more. Thus, relatively low light intensities are required for algae growth and oxygen evolution over long periods of time.

Recent work by Kok[5] and Myers[13], has shown that an intermittent illumination might produce better results than a continuous source of light. In this instance, higher intensities are more efficient. The algae are illuminated for 2 milliseconds, and are in the dark for 20 milliseconds at about 5,000 f.c. of light.

Chlorella and Scenedesmus have been used most for experimentation because of their ready availability, but other algae may be more proficient in producing oxygen. Myers has found that a given mass of Anacystis nidulans, a blue-green alga found in Texas ponds, has a potential oxygen evolution three times greater than an equal mass of Chlorella pyrenoidosa but in order to obtain this amount of oxygen, Anacystis can absorb, and must be illuminated with three times as much light as chlorella.[11] With this alga, then, there is in the possibility of obtaining a surplus of oxygen, using the same mass of algae, as in the case of Chlorella, or of being able to use only one-third the mass of algae to produce the same quantity of oxygen. In the sealed cabin of a space ship this could be a very important factor because of the space required in the craft for the algal equipment.

Little is known, at this time, regarding the potentialities of Anacystis in other directions. Should these possibilities be limited, perhaps a mixture of Anacystis and Chlorella could be used advantageously.

The removal of carbon dioxide is just as important as the rate of oxygen production with algae. Since five pounds of Chlorella can absorb the carbon dioxide produced by one man, this problem would seem to be solved. In the laboratory Chlorella are aerated with five percent carbon dioxide in air, and apparently can absorb all the carbon dioxide, although the algae can get along on much less. The carbon dioxide in expired air is four percent. In our 100 cu. ft. Space Cabin Simulator at the School of Aviation Medicine, if carbon dioxide is allowed to accumulate from one human without its removal, it will reach about five percent in approximately three hours. Navy research has shown that in order to retain normal mental activity that the carbon dioxide level must be not more than 1.5 percent,[19] preferably lower. With absorption by chemicals, we are able to keep the carbon dioxide level at .5 percent in our Simulator. Carbon dioxide buildup and toxicity becomes a problem, in about one-half the time as does the dwindling oxygen supply, if the latter is not replenished in a sealed cabin.[16]

Can an algal system keep the carbon dioxide concentration at the proper level in a sealed system? Studies designed to answer this question are now in progress by Dr. Myers for the School of Aviation Medicine.

2. <u>Food Production</u> - The potentialities of algae with regard to production of food are quite good, when one considers the chemical composition of Chlorella,[17 18] and Scenedesmus.[21] The average composition of these algae is 50 percent protein, 15 percent carbohydrate, 25 percent lipids, and about 10 percent ash. This makeup varies, of course, with the composition of the nutrient solution. These algae are strongly oriented to protein synthesis and when grown rapidly in thin suspensions the protein may increase to 70 percent or more. Protein content can also be increased by the use of blue light in illumination.[14] When blue light is used, a larger portion of the carbon dioxide and hydrogen is utilized in the formation of protein. High protein synthesis is also caused by high nitrogen content in the nutrient solution.

Chlorella is very efficient in retaining photosynthetic products within the cell, regardless of the amount of illumination. The net result is the formation of new cells and rapid growth. Some algae are capable of doubling their weight twelve times in one day, under optimal conditions. The amount of organic matter thrown off by Chlorella is extremely small, and the same is true of the number of dead cells found in a growing suspension.

Because such a high percent of algal cells is digestible, as has been mentioned already, and the loss in preparing them as food would be almost zero, algae would seem to be an ideal source of food aboard a satellite or space ship, for flights of the order of weeks or months.

Chlorella contains nearly all the amino acids essential for good health with the exception of those containing sulfur. They are grossly deficient in cysteine and moderately deficient with regard to methionine. Histidine content is, likewise, moderately low. Algae contain also, appreciable amounts of carotene, or pro-vitamin A, and of the B complex vitamins and Vitamin C. Vitamin D is not present to any great extent.

Thus, it is apparent that algae can be a very adequate source of protein for man, with the addition of cysteine, methionine, and histidine, and can be at least a partial source of the vitamin requirements.

According to Gaffron,[3] if fifty percent of algae is digestible, two kilograms per day is more than enough to keep a man in good health with mineral and vitamin supplements. If used only as a source of protein in the diet, this amount would be enough for five or six people. Geohegan[4] fed rats which thrived on a mixed diet using algae as a sole source of protein. Jorgenson,[3] in the leper colony at Cabo Blanco, Venezuela, fed algal soups to patients suffering severely from malnutrition and the state of their nutrition was greatly improved.

In theory, then, Myers figure of five pounds (or 2.3 Kg) of chlorella, required to balance the respiratory cycle of a man, would be more than sufficient to supply food for the man for a period of one day, repeatedly, provided the algae doubled its weight in 24 hours. This seems quite reasonable in view of the rates of growth which were given earlier.

This food source also would seem to lend itself to the production of concentrated food tablets, by dehydrating, sterilizing and compressing the algae into bite-sized tablets. Such treatment would enable the crew to store economically, with regard to the space required, a large excess of algal food in the event of an emergency of this nature.

What nutrients are required in the feeding of algae? For the highest protein formation the elements required are nitrogen, carbon, phosphorus and potassium. If the medium is deficient in any one of these, protein synthesis is reduced.[21] If nitrogen is grossly deficient, the growth rate becomes very slow, and the lipid content may increase to as much as 85 percent. As was mentioned before, blue light also increases protein in algae.

Other elements which must be replaced in a nutrient medium are calcium, iron, magnesium and sulfur, and the micronutrients manganese, cobalt, copper and zinc [6,21]. Recent evidence shows that molybdenum may also be very important, as a trace element.[1]

In other words, the same nutrient materials are required for algal growth, as is necessary for higher plant growth. Since this is so, the elements necessary for algal nutrition can be obtained from the most readily available source, namely, human waste.

In a closed ecological system such as a satellite or space ship cabin, human excreta must be disposed of. What better way to do it than to convert it into a reuseable substance, because wherever possible, all matter will have to be converted from one form of potential energy to another, recycling it over and over.

3. <u>Disposal of Human Waste</u> - As if in conformance with the pattern of nature as observed earlier, human waste contains almost exactly the elements required to promote vigorous growth of algae. Nitrogen is abundant in the urine as urea, and comprises approximately 50 percent of the urinary solids. Part of the remaining solids also contain nitrogen. Carbon would be supplied partly from the organic waste of the

gastro-intestinal tract, and in part from the carbon dioxide in exhaled air. Phosphorous, potassium, calcium, sodium, sulfur and magnesium are present in sufficient quantities in the urine to supply the needs of the algae. Some of these are found in semi-solid waste too, including the trace elements required.

From this data, it would appear that the three forms of waste from the human body contain all, or nearly all, the essential elements necessary for growth, respiration, and photosynthesis in algae, and in adequate amounts. For this reason as stated by Gotaas and Oswald[12] at the University of California, it may be considered that sewage is not truly a waste, but contains the low energy forms of every element critical to life. For example, a certain amount of nitrogen is taken into the body and excreted in almost exactly the same amount. If a daily nitrogen balance were made on a normal human, it would be difficult to show any utilization of nitrogen. Only the form and energy level of nitrogenous compounds would be changed. The same is true of the other elements.

Gotaas and Oswald, among many others working in the field of sanitary engineering, have shown that Chlorella will thrive on domestic sewage in open oxidation ponds, and that aerobic bacteria present in these ponds have no detrimental effect upon the growth of the algae. In fact, they aid algal growth by providing carbon dioxide while the algae provide oxygen for the bacteria. These facts may have a very significant effect on certain aspects of our agricultural economy, in years to come. In the pilot plant in California the average annual yield of algae was thirty tons per acre, dry weight, as compared to 1.5 tons per acre annual yield, for the California field crops.[12] Algae feeds have been found to be excellent for livestock feeds.

There is no reason why algae, when prepared adequately for the table, cannot be just as acceptable - yes, even as tasty - as the highly-touted spinach, broccoli, and other green vegetables. In fact, four years ago, algal research scientists prepared and ate a banquet in which all the courses of the meal were composed partially of algae. The event was a notable success.

Summary:

We have seen that, in a closed ecological system such as a spaceship cabin, the possibilities of using algae to attain the three objectives already outlined, are theoretically quite favorable. Although much more data is needed before an algal exchange system becomes a reality, the engineering of such a system, to make it fit in a satellite or space ship, and capable of operating under the environmental conditions which will prevail there, will be as great a challenge as the algal research itself.

The engineering of an algal exchange system must include the following:

1. The means of illumination of the algae using artificial or solar light, or both, with a controlled spectrum most suitable for the algal reaction desired.

2. A method of aeration. Cabin air can be bubbled through the algal suspension. Carbon dioxide and the odor gases will be removed from the cabin atmosphere, by the algae, at the same time.

3. Population density measuring devices - probably photometric - in two or more locations in the system.

4. A means of circulation and causing turbulence of the suspension.

5. Nutrient analysis and nutrient addition devices.

6. A harvesting mechanism, probably employing centrifugation or filtration methods.

In addition there must be a suitable means of preparing the harvested algae as food. Lastly, the human waste will have to be processed suitably in a miniature processing plant, in order to be used as nutrients for the algae, since, in this case it would not be desirable to use unprocessed waste.

It must be remembered that this entire system must be able to operate efficiently in a barometric pressure of approximately one-half an atmosphere, or about an 18,000 foot equivalent, and in the zero-gravity state. In a zero-gravity environment the engineering problems involved will be greatly increased.

- - - - -

REFERENCES

1. Anderson, A.J.: Symposium on Inorganic Nitrogen Metabolism - Johns Hopkins University Press. 1956

2. Cook, Paul M.: Chemical Engineering Problems on Large Scale Culture of Algae. Industrial & Engrg. Chem., Vol. 43, 2385. July-Dec. 1951

3. Gaffron, H.: Food From Algae. Research, Vol. 6, 222-230; 1953

4. Geohegan, J.M.: Experiments with Chlorella at Jeallots Hill

Proc. World Symposium on Applied Solar Energy, Phoenix, Arix. 1955; Stanford Research Inst. Menlo Park, Calif.

5. Kok, Bessel: Photosynthesis in Flashing Light. Carnegie Institute of Washington, Yearbook No. 51: 1951-52

6. Kraus, R.W.: Algal Growth Unlimited: Research Reviews, 6 July 1956

7. Morimura, Y. and Tamiya, N.: Preliminary Experiments in Use of Chlorella as Human Food. Food Technology 8, 179-182.

8. Myers, Jack.: Algae as an Energy Converter. Proc. World Symposium on Applied Solar Energy. Phoenix, Arix. Nov. 1955, Stanford Research Institute, Menlo Park, Calif.

9. Myers, Jack: Basic Remarks on the Use of Plants as Biological Gas Exchangers in a Closed System. J. Av. Med. Vol. 25, pp. 407-411, 1954

10. Myers, J. and Johnston, J.: Carbon and Nitrogen Balance of Chlorella During Growth. Plant Physiology, 24: 111-119, 1949

11. Myers, Jack: Personal Communication. Sept. 1956

12. Oswald, W.J. and H.B. Gotaas: Photosynthesis in Sewage Treatment. Presented before Sanitary Engineering Div. Amer. Soc. Civil Engrs., New York, N.Y., Oct. 1954

13. Phillips, N., and J. Myers: Growth of Chlorella in Intermittent Light. Carnegie Institute of Washington Yearbook No. 51: 1951-52

14. Photosynthesis: Colliers Yearbook 1955. Pg. 549

15. Reay, George A. : The Ocean as a Potential Source of World Food Supply. Food Technology, Vol. 8: 65-69. 1954

16. Roth, E.M. and J.G. Gaume: Experimentation in the Sealed Cabin. In prep.

17. Schlier, LeRoy, L.E. McClure, and M.S. Dunn: Amino Acid Composition of Chlorella. Food Research, 18, 337, 1953

18. Spoehr, H.A. and H.W. Milner: Chemical Composition of Chlorella. Plant Physiology, 24: 120-149, 1949

19. Submarine Medicine Practice: U.S. Navy Bureau of Medicine and Surgery, 1956

20. Tamiya, H.: Growing Chlorella for Food and Feed. Proc. World Symposium on Applied Solar Energy, Phoenix, Ariz., Nov. 1955, Stanford Research Institute, Menlo Park, Calif.

21. Thomas, W.H. and R.W. Kraus: Nitrogen Metabolism in Scenedesmus Obliquus (Strain WH-50) as Affected by Environmental Changes. (Plant Physiology.) 30:2, pp 113-122. 1955