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ALGAE AS AN ENERGY CONVERTER

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This discussion will be concerned with the machine-like characteristics of the algal cell as an energy converter. Two kinds of operations are performed. One is an accumulation of carbon, nitrogen, and inorganic salts. The second and more dramatic is the conversion of the kinetic energy of light into potential chemical energy. The key process is photosynthesis. As in most biochemical machinery the process operates cyclically, Fig. 1. The energetic upgrading of carbon dioxide to carbohydrate is driven by reducing power (H) arising from the photochemical oxidation of water. The further conversions to lipids, proteins, and other materials may be driven in part by photochemical reducing power, but they do not depend upon this alone and may be powered by oxidation of some of the carbohydrate. In most algae all other such syntheses may be accomplished from carbohydrate in the dark.

Although the machinery of the algal cell is not at all completely boxed off into unit operations, it is convenient to distinguish between two types of processes: (1) photosynthesis and (2) the secondary syntheses which depend upon it. The total result is an increase in mass of a cell leading to its walling off and division into a number of daughter cells. This is algal growth: cell machinery is making more cellular machinery. Because of the multiplying character of algal growth we express its rate as a compound interest rate or a first order reaction rate constant (e.g., $\underline{k}$ in the equation $N = N_o e^{kt}$ where $\underline{N}$ is cell number or mass and $\underline{t}$ is time).

Now let us examine the requirements of the algal cell machinery using the particular alga Chlorella as our type case. We must grow the alga suspended in a dilute salt solution. Salt concentrations, particularly of fixed-nitrogen, can be adjusted to give rates of growth far greater than commonly experienced by the alga in nature. Carbon dioxide poses a special problem since it is a major material requirement. One pound of dry Chlorella requires about 1.8 pounds of carbon dioxide. At the yields to be suggested by Professor Tamiya we might produce one pound of Chlorella per day upon 0.01 acre. If we were to use air as our source we would have to scrub all of the carbon dioxide out of 50,000 cubic feet to provide the necessary requirement. You will understand why most workers have chosen to provide carbon dioxide from sources other than air.

Temperature becomes a problem because an algal suspension exposed to direct sunlight must dissipate considerable heat. In areas of the world where the average insolation is high, air and soil temperatures are usually also high and special cooling systems must be devised if the culture temperature is to be kept below 100 degrees F (38 degrees C). The standard Chlorella and most of the algae commonly used are killed by prolonged exposures above about 85 degrees F (30 degrees C). However, there are algae, such as the high-temperature Chlorella isolated by Dr. Sorokin[6] which do grow at temperatures up to 102 degrees F (39 degrees C), Fig. 2. We are confident that the temperature problem can be solved by intensive search for other desirable temperature-tolerant algae as will be indicated also by Professor Tamiya's experiments.

Light is our most important consideration. The spectral response is fairly broad, corresponding closely to the visible region, for our purposes 4000 to 7000Å degrees, Fig. 3. About 40 percent of solar radiation at the earth's surface is available for photosynthesis and algal growth. Response to irradiance or illuminance (or in less rigorous terms, light intensity) is linear, but only up to a rather low limit. A plot of specific growth rate of a very thin suspension of Chlorella as a function of illuminance is given in Fig. 4. Some finite but very small and as yet unmeasured value of illuminance is necessary merely to sustain the overhead of algal metabolism. Beyond this the curve is linear over what is called a light-limiting region and finally levels off to a flat plateau of light-saturation. We shall return later to the important consequences of this curve. First, however, let us examine the efficiency with which our algal machine operates.

Properly we may avoid the currently debated problem of the quantum yield of photosynthesis. We are concerned, not with this partial operation, but with the over-all efficiency of synthesis of new algal material. On this question we have only one published work, that of Dr. Bessel Kok[1]. Using the yellow sodium line, he obtained efficiencies which ranged from 18 to 24 percent under favorable nutrient conditions. Current reinvestigation in our own laboratory by a different technique has shown efficiencies up to 15 percent but we are doubtful that optimum conditions have been obtained. In extrapolation to actual use of the entire visible spectrum there are a number of considerations, some which would increase and others decrease the expected efficiency. For our discussion it is reasonable to adopt a value of 20 percent. This means simply that the production of one gram of dry Chlorella worth 5.8 kilocalories will require 28 kilocalories of absorbed light energy. If we wish to extrapolate further to use of total solar radiation we must consider that the visible region includes only about 40 percent of the total insolation; our efficiency for use of total solar radiation then becomes 8 percent.

Unfortunately, still another problem enters when we attempt to use algae as solar-energy converters. Let us return to the curve of growth rate as a function of illuminance. Along the light-limited portion the efficiency is maximal and nearly constant; it is here that efficiency measurements such as those of Dr. Kok are made. As soon as an algal cell gets exposed to illuminancies beyond the light-limited region some of its machinery cannot keep pace with the basic photochemical process; an increasing fraction of the light is dissipated as heat and the efficiency goes down. Now if we put in actual values of illuminance we find that the light-saturation point for Chlorella occurs at an uncomfortably low level of about 500 foot-candles (white light) as compared to a maximum solar illuminance of 10,000 foot candles. We face a difficulty exactly the opposite of that encountered with most solar converters: here instead of the energy flux being too low it is far too high. The machinery of an algal cell is geared to a rather low rate of energy input.

In order to obtain maximum yields in actual algal culture we shall want to manage so that all of our incident light is absorbed. The illuminance in the culture will fall off roughly according to Beer's Law as the exponential decay shown in Fig. 5. This characteristic tells us two things. First, the depth of the culture and the cell concentration are reciprocal functions. It has been shown that if the thickness is reduced to about one centimeter, the cell concentration may be raised to a value of 50 gm/liter[3]; conversely, in deep ponds maximum concentrations far less than 1 gm/liter may be expected. Attainable cell concentrations are of importance since they control the economics of harvesting procedure.

A second consequence of the above curve is a further reduction in actual efficiency of use of sunlight. A cell at the front surface absorbs light at a rate proportional to 500 foot-candles. We will abridge the argument here to the following result: the total light absorption by the culture is proportional to the area underneath the curve; of this the fraction used with maximum efficiency (i. e., 20 percent) is proportional to the smaller shaded area. Observed yields under sunlight are lower than yields calculated from a 20 percent efficiency by a factor of 5 to 10 times. We see here the consequence of the low light-saturation point. Attempts to make important gains in yield per unit area must be directed toward this problem. Efforts have been made or are being made in three directions: (a) the use of turbulence of culture to produce advantageous intermittent light effects as viewed by individual cells; (b) the use of light diffusers designed to spread the high surface illuminance over a greater area in the horizontal dimension of a deep culture; and(c) the search for algae with equal efficiencies but higher levels of light saturation.

Now let us turn to the product characteristics of the algal cell machine. The critical point here is that the product of the algal cell is more algal cells, a multiplication of biochemical machinery.

In Chlorella materials excreted into the media amount to only a few percent of the new cells produced.[2] We do not know and hardly expect to find in any alga a normal metabolism in which the cell machinery is relatively static and a useful product is excreted in a way analagous to the production of ethyl alcohol by yeast. By the same token, the production of growth-limiting inhibitors, though reported for one strain of Chlorella, does not appear to be a general algal characteristic.[2] A consequence of the almost exclusive multiplication of new algal cells, rich in biochemical machinery, is that the product is high in protein (about 50 percent), in chlorophyll (about 5 percent) and in vitamins.

What can we anticipate in product use? There are three possible economic levels: for energy, for food, or for special organics. The use of algae as a fuel for energy does not seem very attractive for three reasons: (a) except for the blue-green nitrogen-fixing algae, the high requirement of fixed nitrogen makes the system almost prohibitive energetically, (b) there is the problem of drying out the 75 percent water content of fresh cells, and (c) the high protein content is remarkably dear to be used as a fuel. The use of algae as food is entirely reasonable, though not considered practical in the United States at present cost estimates. For the production of special organics of high market value the synthetic capacities of the algae offer attractive possibilities as yet almost unexplored.

Finally, let us re-examine the earlier simplification which led us to base this discussion upon the single alga Chlorella. In the area of large-scale culture Chlorella has become almost synonymous with algae. Actually, we should regard Chlorella only as a type case; it is an algal

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weed chosen because it is hardy and easily grown and because of the greater initial background information. There are many kinds of algae about which our knowledge is exceedingly scanty. We must explore for species with growth characteristics and products of particular usefulness. In this area of the microbiology of the algae we may look for advances at least as significant as in the area of engineering design.

In closing, it is only proper that a clear statement of acknowledgement be made to the Carnegie Institution and to Dr. Vannevar Bush for the impetus which has been given in many ways to the study of possibilities of large-scale algal culture.

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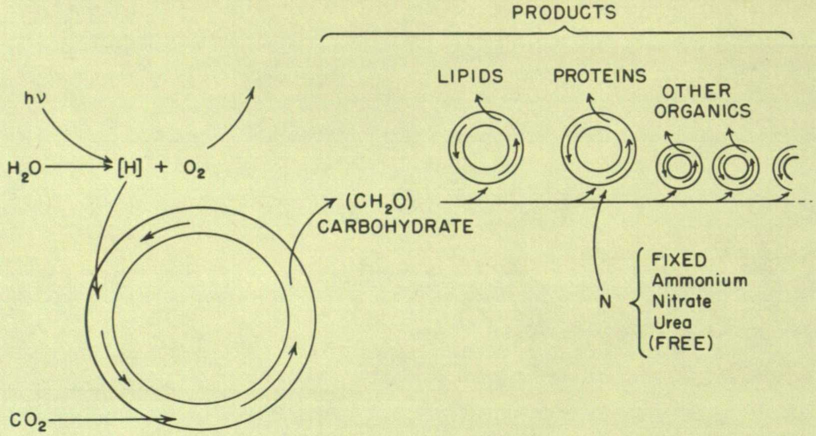

FIG. 1

SYNTHETIC MACHINERY OF THE ALGAL CELL PRESENTED DIAGRAMMATICALLY

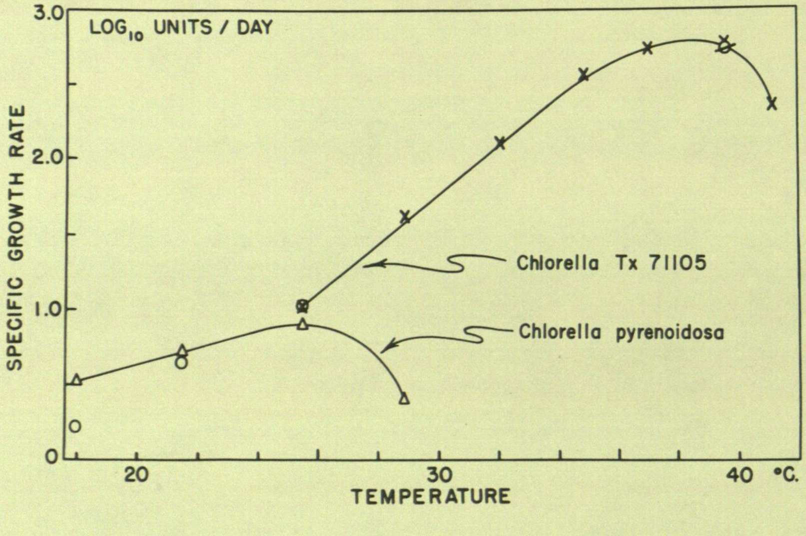

FIG. 2

GROWTH RATE AS A FUNCTION OF TEMPERATURE FOR TWO SPECIES OF CHLORELLA AT LIGHT SATURATION (6)

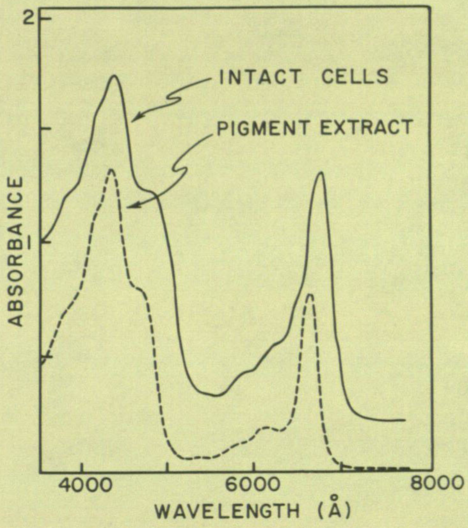

FIG. 3

SPECTRAL ABSORPTION CURVES FOR CHLORELLA. THE UPPER CURVE FOR INTACT CELLS IS PARTLY, BUT NOT ENTIRELY, CORRECTED FOR SCATTERING EFFECTS. REDRAWN FROM (5)

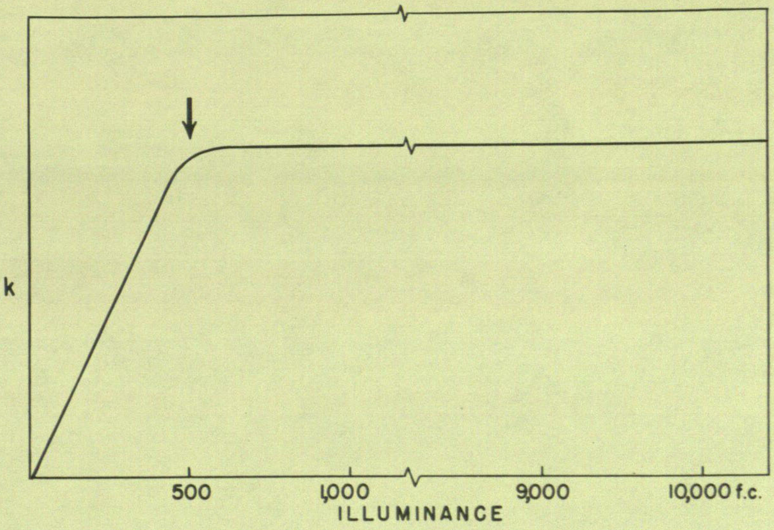

FIG. 4

GROWTH RATE AS A FUNCTION OF ILLUMINANCE FOR A THIN SUSPENSION OF CHLORELLA PYRENOIDOSA. REDRAWN DIAGRAMMATICALLY FROM (4)

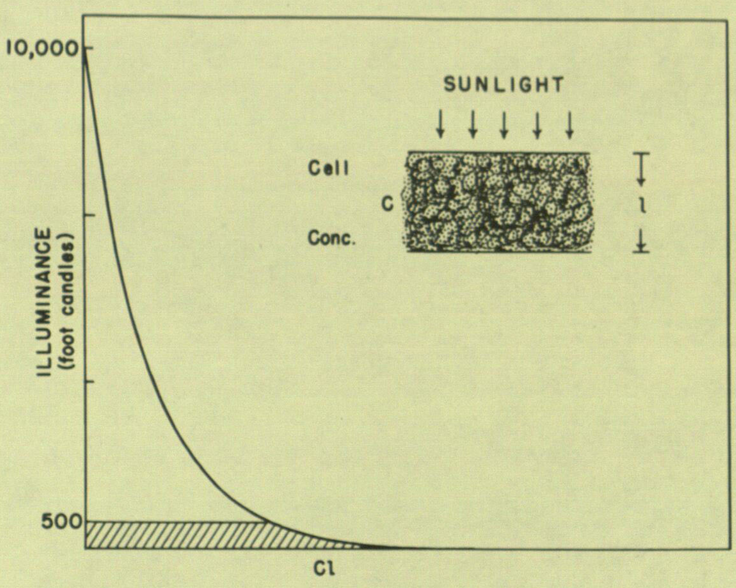

FIG. 5

DECREASE IN ILLUMINANCE IN A DENSE CULTURE
EXPOSED TO FULL SUNLIGHT