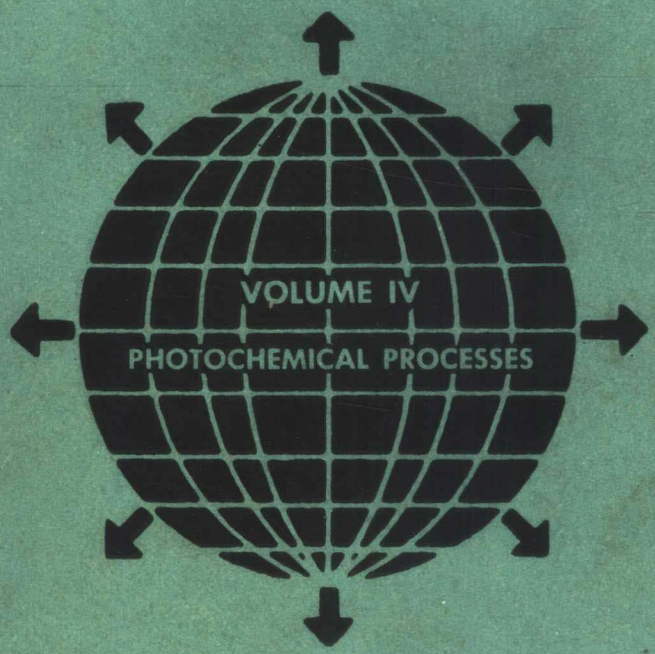
TRANSACTIONS OF THE CONFERENCE ON THE USE OF SOLAR ENERGY

THE SCIENTIFIC BASIS

TUCSON, ARIZONA
OCTOBER 31 - NOVEMBER 1, 1955



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STANFORD RESEARCH INSTITUTE

ASSOCIATION FOR APPLIED SOLAR ENERGY

INTERNATIONAL CONFERENCE on the USE OF SOLAR ENERGY– THE SCIENTIFIC BASIS

TRANSACTIONS OF THE CONFERENCE

Held at Tucson, Arizona, U. S. A.

October 31 and November 1, 1955

VOLUME IV

Photochemical Processes

Sponsored by

UNIVERSITY OF ARIZONA
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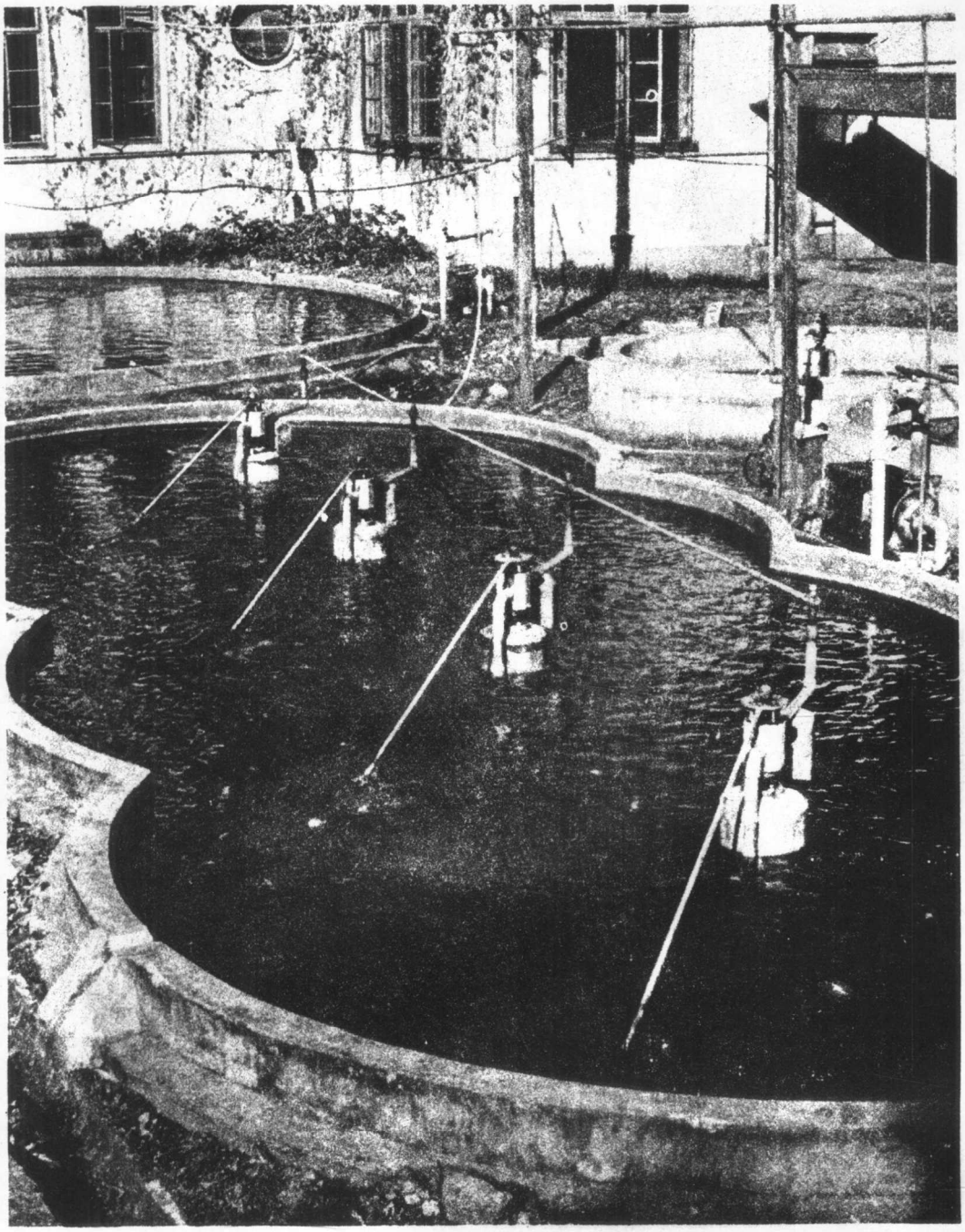

Mass culture of algae at the Tokugawa Institute for Biological Research at Tokyo

Photograph courtesy of H. Tamiya

PREFACE TO VOLUME IV

The purpose of Section B was to review the available information on prospects of fixing solar energy by photochemical means. Since the photosynthesis of green plants constitutes man's only means of utilizing solar energy in significant amounts through photochemical processes, it is understandable that most of the papers are concerned with photosynthesis.

Apart from the fossil products of photosynthesis (coal, petroleum, peat, etc.), crop plants and timber trees have been the only important means available to mankind for direct exploitation of photosynthesis, from the dawn of history up to modern times. In recent years, however, there has been speculation that the culturing of algae might be developed on a scale sufficient to become a new means of utilizing solar energy. This possibility is being studied in a number of laboratories, in widely separated parts of the world. It is too early to predict whether the greatest potentialities of algal culture lie in the direction of food production, livestock feeds, treatment of sewage wastes, chemurgic products, or of still unforseen applications. The diversity of contributions dealing with problems of algal culture and utilization of products is evidence that many avenues of approach are being explored, and that the subject is receiving the attention it deserves.

Under the chairmanship of Dr. Milner, aspects of algal physiology relevant to the problems of large-scale cultivation were presented for discussion. Then followed, under the chairmanship of Dr. French, a series of contributions on various practical aspects of large-scale cultivation of algae, intended to demonstrate the potentialities of algae for a wide range of purposes.

The papers on algae justify the expectation that the current, rather high, estimates of the cost of large-scale cultivation will be reduced, as better methods are introduced. There is a possibility that certain products from algae may become competitive with products from conventional crop plants. It seemed important to consider whether substantial improvements in the productivity of crop plants, and in the extraction and utilization of their products, are to be anticipated. Under the chairmanship of Dr. Emerson, some genetic and biochemical factors of importance in connection with crop plants were reviewed, and prospects for improvement were discussed. Then followed several papers dealing with recent advances in knowledge concerning the part played by chloroplasts and by plant pigments in photosynthesis, and a discussion of photosynthesis and the production of organic matter, in relation to photochemistry.

The possibilities of utilizing photochemical processes other than photosynthesis for exploitation of solar energy have received but little attention, but a better understanding of photosynthesis could conceivably lead to important developments in photochemistry. It was therefore appropriate to include in the program some contributions dealing with photochemical processes other than photosynthesis. There were reports on the utilization of sunlight in the preparation of certain organic substances, and on photogalvanic cells as a means of storing light energy.

The program of Section B was terminated by Dr. Rabinowitch's review of the general problems of photochemical energy storage and future prospects, in the light of present knowledge concerning photochemistry as well as green-plant photosynthesis.

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Section on Photochemical Processes.

University of Illinois,
Urbana, Illinois.

Carnegie Institution of Washington,
Stanford University, California.
July 1956

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CHAPTER 1.

ALGAL GROWTH: PROCESSES AND PRODUCTS

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I address this discussion to two rather limited areas of algal physiology which one must regard as of critical importance to applied large scale culture of algae. The first of these will have to do with the light factor and the efficiency of utilization; the second will be concerned with the nature and possibilities of control of the algal product.

We must regard the algal cell as a light powered machine whose essential business is the production of more cellular machinery. In nature, rate of operation is usually limited by availability of raw materials, and the algae are not notable for accumulation of concentrated masses of organic material. Yields per unit surface area are always small. Very great increases in yield are accomplished by increases and adjustment of nutrient salt concentrations, provision of carbon dioxide, and control of temperature-problems to be discussed in the following paper by Dr. Krauss. When all nutrient requirements are adjusted to optimum levels, yield becomes limited by the rate of input light energy and the efficiency with which it is used. Our problem is to find how algae can utilize solar energy most efficiently.

A base point for our discussion is the limiting or maximum efficiency achievable. We are concerned here, not with the question of efficiency or quantum yield of photosynthesis, but with the efficiency of over-all algal cell synthesis. We have but one published work, that of Kok (9). In experiments with Chlorella carried over about three days duration and in illumination with the yellow sodium line he obtained efficiencies in the range of 18 to 24 percent under favorable nutrient conditions. Because of the importance of this value we are currently engaged in further investigation in our laboratory. We are using a steady-state system in which growth rate, cell production, oxygen, and carbon dioxide exchange may be followed simultaneously in experiments of 5 to 10 days duration. Our initial experiments using the yellow and green mercury lines, have given efficiencies of about 15 percent for Chlorella pyrenoidosa but we are doubtful that optimum conditions have been obtained. In extrapolation to use of the total visible region some decrease in efficiency must result from the higher energy per quantum in the weighted wave length distribution. At the same time some increase in efficiency is to be expected when ammonium or urea is used as a nitrogen source in place of the nitrate in Kok's work and in our initial experiments. For our discussion I shall adopt 20 percent as a reasonable maximum value of efficiency for use of white light.

In contrast to the rather high maximum efficiency, the efficiencies actually observed in large cultures under sunlight illumination (e.g., Wassink, Kok, and Oorshot (18)) are far lower and in the general range of 2 to 3 percent; in fact they are no higher than those recorded for crop plants under most favorable conditions (18). In short, there exists a discrepancy of a factor of ten between the maximum efficiency and those observed in actual cultures under sunlight intensity. A portion of the discrepancy may be laid to the greater elegance of control and maintenance of favorable conditions possible in small laboratory cultures. However, there is general agreement that the major portion of the discrepancy lies in the very high light intensity of sunlight and the difficulty of light saturation.

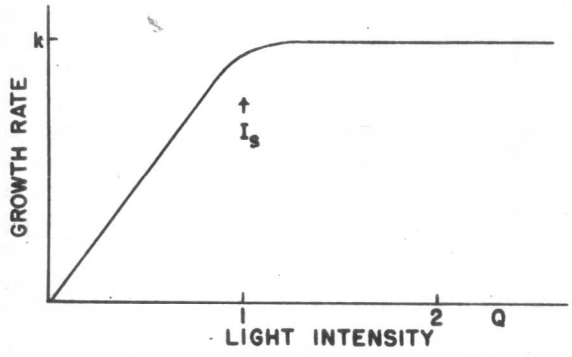
As observed in thin cultures the specific growth rate of Chlorella pyrenoidosa is a function of light intensity as shown somewhat diagrammatically in Figure 1. Our data lead us to draw a simple light saturation curve. Tamiya (17) prefers to present his data as fitting better to a hyperbolic curve. The form shown here submits more simply to the graphical treatment which I shall use although either approach will lead to the same essential result. Further I shall express light intensity or irradiance in the conceptually simple units of Q, so defined that a Q represents 10^9 quanta per Chlorella cell cross section per second. The essential feature of the curve is that light saturation occurs at a light intensity I_s about 1/20 of the maximum intensity of sunlight. Up to about 1 Q a cell works at maximum efficiency; at higher intensities the cell may absorb quanta at a rate proportional to intensities up to 20 Q, but it works no faster than at 1 Q. The consequences are seen in Figure 2. In a culture illuminated at maximum sunlight of about 20 Q the light intensity falls off exponentially, the total area under the curve being proportional to the absorbed 20 Q; but the cells in the first layers can work no harder than at a rate proportional to 1 Q. The net result is that the absorbed light actually used for growth is that fraction of the total represented by the lower shaded area as a fraction of the total area. From the point of view of energy budget one can say that energy proportional to the shaded area, in this case about 4 Q, is used with maximum (20 percent) efficiency and that the remainder is used with zero efficiency.

It will be seen that the fraction of absorbed light used with maximum efficiency depends upon the relation between I_s and the incident intensity I_o. From the same arguments used here Bush (cited by Burlew (2)) has derived an equation for the fraction f of light used at maximum efficiency

$$f = \frac{I_s}{I_o} \left(\ln \frac{I_o}{I_s} + 1 \right)$$

A plot of f as a function of I_s/I_o is shown in Figure 3. The value of f approaches unity and over-all efficiencies approach maximum efficiency as I_s approaches I_o.

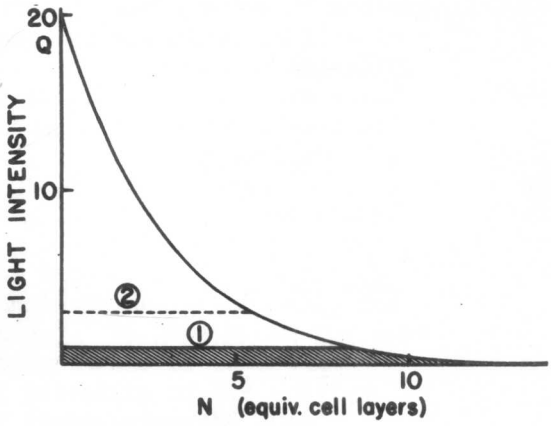
By various investigators, more or less independently, three ways of increasing the over-all efficiency or yield per unit area have been suggested. The first depends upon selection of algae with higher values of I_s. If, for example, we can find a strain with a higher light-saturated growth rate but the same light absorption, as seen in curves 2 of Figure 2, then we would be able to raise the over-all efficiency.



Q in quanta per cell per sec. x 10^{-9}

FULL SUNLIGHT (visible) ≡ { 20 Q ; 0.70 cal. $cm.^{-2}$ $min.^{-1}$; 10,000 f.c. }

FIG. 1



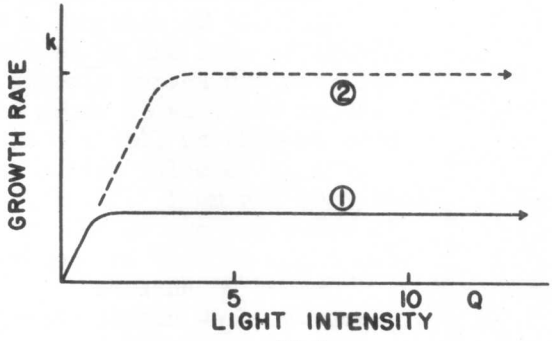


FIG. 2

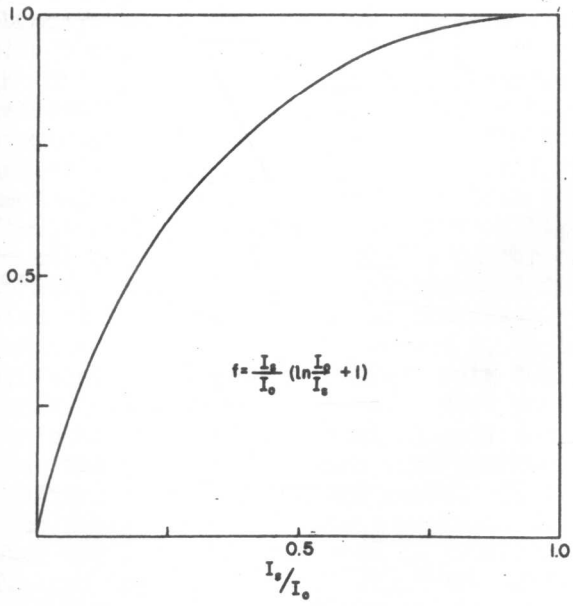


FIG. 3

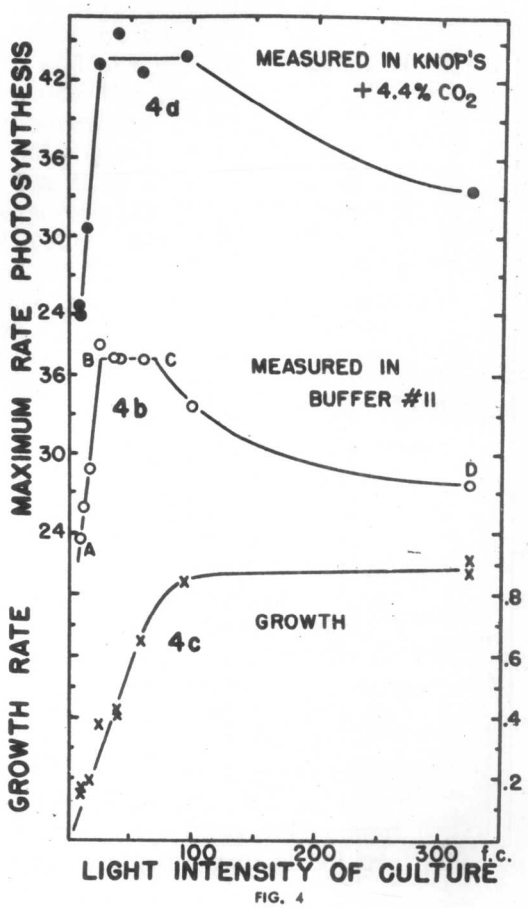


FIG. 4

In attempts to predict the over-all efficiency to be expected of a given alga there is a limitation which has not been noted previously. It lies in the fact that the light intensity curve of growth has an important parameter which has not been specified. To obtain data on which the curves are based one sets up a steady-state system and measures the specific growth rate at each light intensity. In an actual mass culture growing under sunlight the specific growth rate may be very small. Our argument has required that any one cell moving at random in a dense culture and growing at low rate has an instantaneous growth rate response described by the curve obtained under a series of steady-state conditions. Now we cannot measure an instantaneous growth rate as growth but we can measure it as photosynthesis (actually the apparent photosynthesis uncorrected for respiration). We have known for some ten years that the light intensity curve of photosynthesis of Chlorella pyrenoidosa varies systematically with the light intensity of its previous culture (12). Figure 4 is a plot of the rate of light-saturated photosynthesis measured in short-time experiments, as a function of the light intensity at which it had been cultured, and compared to the rate of growth. The only point at issue here is that the photosynthesis curves are not flat but show severe variation, particularly for cells grown at very low rates. The curves illustrate the problem although they do not tell us what we need to know. We need to find an alga which maintains a high value of I_s even when grown in dense cultures at low specific growth rate. I am not sure that we shall find such an alga, but the stakes are high and we are now aware of the characteristics for which we must search. It appears that we might make a simple selection by growing cultures of mixed algal strains in dense cultures under high light intensity and selecting the strain which becomes predominant.

A second possible means of increasing over-all efficiency lies in utilizing the intermittent light effect by turbulence of culture. If we stir a dense culture so violently that cells move into and out of the illuminated front surface very rapidly, they might be able to use the short bursts of light with high efficiency. We know from many theoretical studies of photosynthesis that such an effect occurs. The only question is how the effect may be manifest in total growth and what the time characteristics of intermittency must be. We have reported such measurements (15) the essential results of which are shown in Figure 5. I shall follow the interpretation previously proposed by Kok (10). The focused and uniform light beam had an intensity about 2/3 that of full sunlight. If the intensity is cut by use of neutral screens there obtain the data shown by the solid line and labelled "continuous." Instead of continuous light regulated by screens we now use a rotating sector with a variable number of openings. The number and size of openings controls its time-integrated transmission; the angular velocity and size of the openings control the flash time. With lengthening flash times we obtained successively the curves D, C, B, and A. If a cell were to photosynthesize and grow at maximum rate during the light flash only, with no carry-over into the succeeding dark period we would expect the curve OX. At the other extreme, if an algal cell completely integrates intensity X time and uses the very bright flash with maximum efficiency, then one expects superposition on the continuous curve. It is seen that there is almost complete time integration and almost maximum efficiency in use of high light intensity when the light is presented in flashes as short as 0.001 second. With longer flashes approaching 0.1 second the degree of integration and efficiency go down. From such results we must conclude that very likely some small contribution of the flashing light effect occurs in any stirred algal culture. However, any large gain factor would seem to require light flashes so short and a turbulence so great that the gain would be offset by increased power consumption. The same conclusion may be reached from other studies by Kok (10) and by Davis (3).

A third approach to the problem is to manipulate the incident intensity I_o so that it approaches I_s. We can do this usefully only by spreading incident sunlight over an area of culture greater than the ground surface area. One suggestion of Woods (cited by Burlew (2)) is the use of surfaces inclined toward the mean position of the sun so that a thin layer of culture flowing over them would be exposed to oblique illumination of lower intensity. This poses some severe technical difficulties. A second suggestion made by Evenari, Mayer, and Gottesman (4) requires use of vertical transparent tubes penetrating a deep culture and containing reflecting cones, base down, to reflect the light horizontally into the culture. I understand from Professor Evenari that because of construction difficulties this proposal has not been tested.

Consideration in this area has led us to a third variant with a number of potential advantages over the design of Evenari et al. We propose the use of diffusing cones with their bases at the illuminated surface as illustrated in Figure 6. Simple geometry shows that when the length of the cone is 5 times the diameter of the base, the diffusing area of the cone becomes 10 times the area of the base. A tank of algae fitted with such close-packed cones would have 1/4 of its volume occupied by the cones and 3/4 of the surface area covered by the cone bases. Numerous variations in geometry are possible. Pyramids or square-based cones could be packed to utilize the entire surface area. Bases of the cones can be modified for best compromises in light-collecting characteristics. It is possible that the inclined diffusing surfaces might better have curved rather than straight-line contours.

In order to test the idea we have devised an apparatus to obtain maximum sunlight intensities for laboratory experiment. The optical system shown in Figure 7 presents a crudely collimated and reasonably uniform focused beam 5 cm. in diameter. Light from a tungsten projection lamp operated at reduced voltage is condensed to an image and collimated by a second lens which also focuses the uniformly illuminated plane of the projection lens onto the culture. Voltage to the lamp is adjusted manually to obtain a constant reading of a monitoring photocell. The light beam is reflected through a fixed 5 cm. diaphragm onto the culture with or without the cone in place. The chamber is surrounded with a nickel plated tube which contains all of the light beam and masks out stray light. Experiments with the apparatus are now in progress. First attempts have used a cone turned from a lucite rod. Other materials and types of geometry are to be tested. In addition to the immediate objective of testing the diffusing cone it is our intent to examine experimentally the relations between I_o, I_s, and cell yield.

The second portion of this discussion will be concerned with the nature and possible variability and control of the algal product. A starting point is the repeated observation that Chlorella and Scenedesmus excrete so little organic matter that 90 to 100 percent of the carbon assimilated may be recovered in the cells produced (11, 14). This means that the algal product becomes nearly identical with Chlorella cell composition. In terms of gross composition we have the extensive work of Spoehr and Milner (16), studies of protein composition by analysis and animal feeding experiments, and studies of the lipid fraction. In addition we have data on other minor constituents of various algae, many of them exotic or biochemically unusual. This information has been compiled in Fogg's monograph (6) and in the Carnegie Monograph (1) by chapters of Milner and others. Further review here would be inopportune.

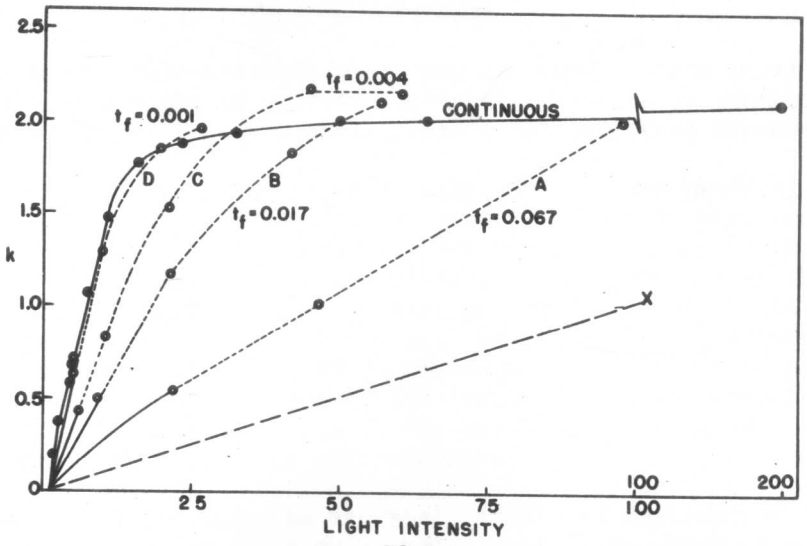
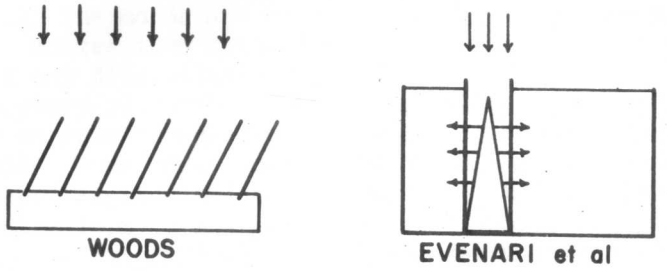


FIG. 5



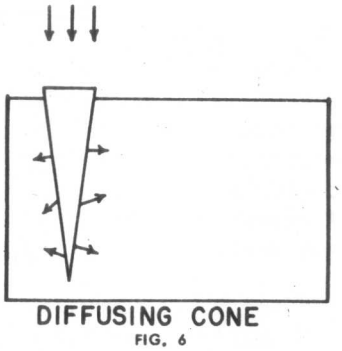


FIG. 6

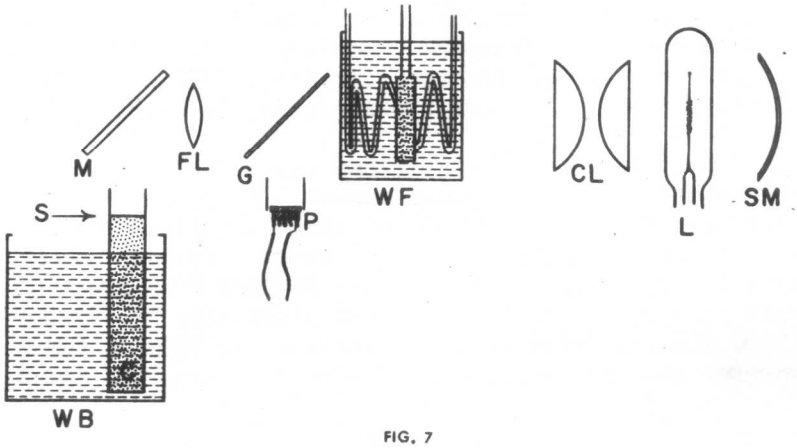


FIG. 7