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The Effect of Light Intensity and Thickness of Culture Solution on Oxygen Production by Algae

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ABSTRACT

Data from a small cylindrical culture unit with variable annular culture chambers indicate that: (a) the rate of oxygen evolution by an algal culture in the linear phase of growth is a logarithmic function of light intensity, and (b) the rate of oxygen evolution per unit volume of suspension is linearly related to the reciprocal of culture thickness. These two relationships have been combined in an empirical equation, which gives the expected variation of the oxygen production rate with light intensity, culture thickness, and suspension volume. The applicability of this equation has been tested on a larger, multi-light culture unit in this laboratory. The agreement between the experimental and calculated oxygen production rates was very satisfactory, suggesting that the equation is not limited to a particular culture unit but may have wide applicability.

The efficiency of the culture unit from the viewpoint of electrical power utilization has been calculated, and it was found that the maximum conversion of electrical energy to chemical energy based on oxygen evolution was only 0.51 percent. The maximum efficiency in converting light energy to chemical energy was approximately 12 percent.

An extrapolation of the experimental results suggests that approximately 2 cubic feet and 30 kilowatts would be required to provide for the oxygen needs of one man.

PROBLEM STATUS

This is an interim report; work is continuing on the problem.

AUTHORIZATION

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THE EFFECT OF LIGHT INTENSITY AND THICKNESS OF CULTURE SOLUTION ON OXYGEN PRODUCTION BY ALGAE

INTRODUCTION

To determine the feasibility of using an algal system for providing oxygen and absorbing carbon dioxide in nuclear-powered submarines, one must know how oxygen production is influenced by the quantity of light made available to the cells. The relationship between oxygen production and light availability in light-limited cultures depends upon several variables, the most important ones being: the intensity of the incident light, the distance the light must penetrate the culture, commonly called the culture thickness, and the illuminated area.

One might expect that cell concentration would affect oxygen production of a culture because mutual shading by the cells changes with cell concentration, thereby changing the amount of light energy reaching each cell. However, by definition, the growth rate of cultures in the linear phase of growth* is independent of cell concentration. Past experience at this laboratory has shown that within the range of cell concentrations used in this study the oxygen evolution rate is essentially independent of cell concentration even when no correction is made for respiration (1). Therefore, in this study cell concentration was not considered an important factor in determining oxygen production.

The effect of light intensity on the rate of oxygen evolution by cultures in the linear phase of growth has been studied previously (1); oxygen production increased logarithmically with light intensity in the range of light intensities considered (4000 to 17,000 foot-candles). The study reported here confirms that finding, but shows also that the logarithmic relationship between light intensity and oxygen production at our concentration range does not hold at low light intensities, i.e., below about 3000 foot-candles.

Tamiya et al. (2) investigated the effect of culture thickness on algal growth rate using flat oblong culture cells and found that for cultures in the linear phase of growth the rate of increase of cells per liter of suspension was inversely proportional to culture thickness. This means that the rate of increase of cells per unit illuminated area was the same for all culture thicknesses tested. It may be concluded from this observation that, under certain conditions at least, algal growth rate depends primarily upon light intensity and illuminated area, if the culture is in the linear phase of growth.

The main purpose of the present study was to obtain the same type of information regarding the influence of culture thickness on the rate of oxygen evolution. The test vessel was a cylindrical culture unit having annular culture chambers of several thicknesses. The oxygen production at five culture thicknesses, varying from 1.0 to 2.9 cm, was determined. The results indicated that at given intensities, the rate of oxygen production per unit volume of suspension was linearly related to the reciprocal of the culture thickness. This relationship has been combined with the logarithmic relationship between oxygen production and light intensity to give an empirical expression showing how oxygen production changes in this culture unit with light intensity, culture thickness, and illuminated area. Thus, the oxygen evolution rate has been related to the three most

*A culture is in the linear phase of growth when the mass of the cells increases linearly with time. This occurs only if a culture is not saturated with light. It is in this phase that the oxygen evolution rate is greatest for a given light intensity.

important factors if growth is limited only by light. The empirical equation has been used to predict the oxygen production rate of another culture unit in this laboratory, and although the geometry of this culture unit differed considerably from the one used in this study, the agreement between the calculated and experimental values was excellent. It appears, therefore, that the equation is not strictly limited to a particular culture unit but may have wide applicability.

From these and other experiments carried out at this laboratory, it seems that the feasibility of using an algal system in nuclear submarines depends mainly upon the electrical power and space requirements of such a system. An extrapolation of the results of this study suggests that an algal system would require about the same amount of space as the present method of supplying oxygen in these submarines, but would consume about forty times more electrical power.

EXPERIMENTATION

Culture Unit

The basic design and operation of the culture unit used in this study are very similar to those described in a previous report (1). As shown in the schematic diagram in Fig. 1, the apparatus is cylindrical and the suspension is contained in an annulus surrounding the light source (described in a later section). Since the primary objective of this study was to determine the influence of culture thickness on oxygen production, the unit was designed so that the width of the annular culture chamber could be changed by using different cylinders. As shown in the top view in Fig. 1, several culture annuli widths were possible, in the range of 1.0 to 2.9 cm.

In addition to the culture chamber, two other annular spaces ordinarily were used in the operation of the apparatus, one on either side of the culture annulus. Water was continuously passed through the innermost annulus to dissipate some of the heat emitted by the lamp. The annulus surrounding the culture chamber was used to control the temperature of the suspension; when the temperature of the suspension reached 38.5°C, a relay opened a solenoid valve, allowing water to flow through the annulus, cooling the suspension. Figure 1 shows that the 2.2- and 2.6-cm annuli extended to the outermost limit of the culture unit making it impossible to have an annulus around the culture chamber when they were used. For these two culture chambers, the temperature of the suspension was controlled to some extent by passing water through the annulus surrounding the lamp as was done for the other culture chambers. The temperature of the suspension was controlled more precisely, however, by sending in an extra surge of water under thermostatic control through the same annulus when the temperature reached 38.5°C.

The suspension was stirred by means of a centrifugal pump (Eastern Industries Model D-11) placed beneath the unit. The suspension was withdrawn from the bottom of the culture annulus through the pump and back to the annulus through a right-angle tube positioned in the base plate. The force of the liquid coming from this tube imparted a rapid swirling motion to the suspension, preventing any large accumulation of cells at the bottom of the culture chamber. Stirring was less vigorous when the smallest (1.0 cm) culture width was used, so there was a greater tendency for the cells to settle out and to stick on the walls of the culture chamber.

An inherent disadvantage of this culture unit for determining the effect of culture thickness on oxygen production was that not all the culture chambers were equidistant from the light source. In a cylindrical unit such as this one, the oxygen production of a culture obviously depends upon the position of the annulus in the unit because light intensity, illuminated area, and suspension volume all change with the distance of the culture chamber from the light source. As a given culture annulus is moved closer to the center

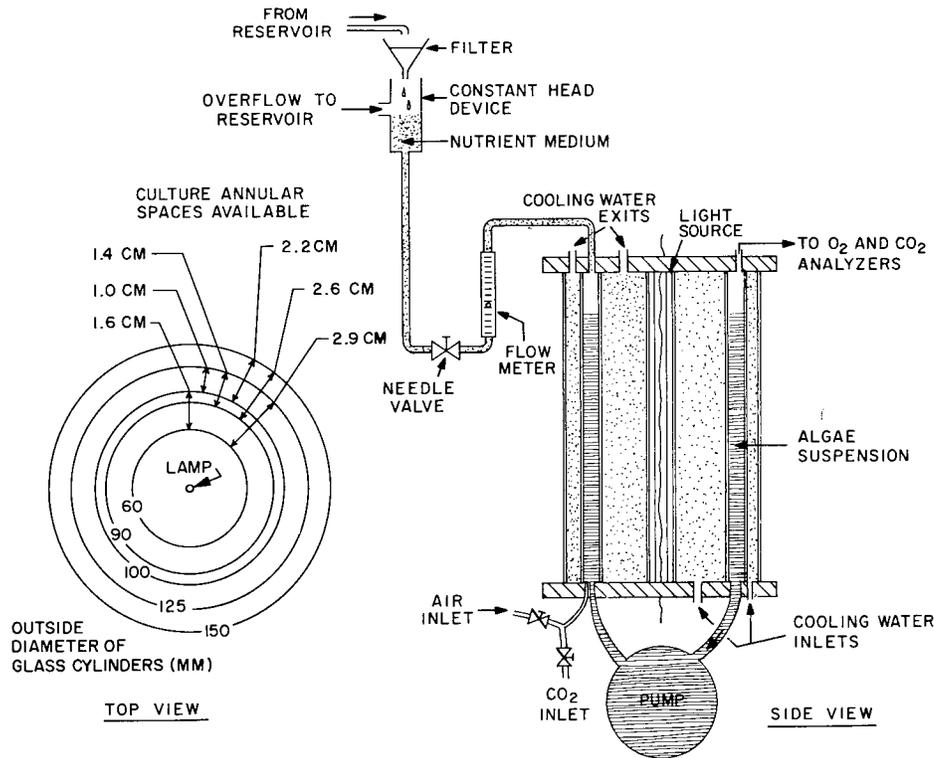


Fig. 1 - Schematic diagram of culture unit

of the unit, the higher light intensity tends to increase the oxygen output but, at the same time, the decrease in illuminated area and suspension volume lowers the oxygen production. Ideally all the culture chambers would be the same distance from the center of the unit, for only then could the oxygen productivities of the various culture chambers be compared directly. The shortcoming of the unit has been overcome to some extent by computing the oxygen output of each culture chamber on the basis of the same volume of suspension.

Gas Supply

A mixture of about 3.5% carbon dioxide in air was introduced to the suspension through a small tube placed immediately in front of the tube coming from the circulating pump. The turbulence of the suspension coming from the tube facilitated dispersion of the gas in the suspension. After passing through the suspension, a portion of the gas was withdrawn by an aquarium pump and sent through a drying column into an infrared carbon dioxide analyzer (Mine Safety Appliances Model 300) and a paramagnetic oxygen analyzer (Beckman Model F-3). These analyzers were connected to a multipoint Brown recorder so that the concentrations of these gases in the effluent gas were plotted continuously. The flow rate of the gas was measured by sending the gas directly from the culture unit into a wet test meter. Because ambient conditions were constant, no correction was made for the water vapor in the gas. At the flow rate used, usually around one liter per minute, and at the carbon dioxide concentration used growth was not CO₂ limited. The observed oxygen evolution rates were not corrected for respiration, and unless noted, all gas volumes are reported for room temperature and pressure.

Light Source

A General Electric incandescent lamp, Model 1500 T3Q/C1, served as the light source. This is a high-intensity lamp consuming 1500 watts at its rated voltage of 277. The intensity of the incident light was easily changed by varying the voltage on the lamp by means of an autotransformer, and was measured prior to the assembly of the culture unit by a Weston foot-candle meter, Model 614, with the use of neutral density filters. The available culture annuli were located 2.9, 4.5, and 4.9 centimeters from the lamp so three ranges of light intensities were used.

In this study it was of interest to know how light intensity falls off with distance. The law of inverse squares would not be expected to be applicable since this lamp is not a point source of light. Instead, the light is radiated laterally so that the illuminated area should increase with distance in the same way that the curved surface area of a cylinder, surrounding the light source, increases with distance. The surface area, A , of a cylinder is proportional to the height, h , and radius, r ,

$$A = 2\pi r h. \quad (1)$$

Thus the light energy falling on a unit surface area of a cylinder of a given height is inversely proportional to the radius. As expected, a straight-line relationship was found between light intensity and the reciprocal of distance as shown in Fig. 2. This may be expressed mathematically by

$$I_0 = \frac{k}{r}, \quad (2)$$

in which I_0 is the light intensity in foot-candles* and k is a constant whose value depends upon the lamp voltage. As a check on the accuracy of the meter used to measure the light intensities, the lumen output of the lamp according to the manufacturer was used to calculate the light intensity in foot-candles as a function of distance. If the illuminated area is known, lumens can be easily converted into foot-candles according to lumens/ft² = foot-candles. Since the lamp was 0.705 ft high and the illuminated area varies with distance r according to Eq. (1),

$$A = 2\pi r h = (6.28)(0.705)r = 4.43 r \text{ ft}^2. \quad (3)$$

For purposes of illustration, the light intensity at 0.0984 ft (3 cm) may be calculated for a lamp voltage of 220. According to the manufacturer of the lamp, 15,700 lumens are emitted at this lamp voltage, and according to Eq. (3), the illuminated area is 0.436 ft². Converting from lumens/ft² to foot-candles we see that 15,700 lumens/0.436 ft² = 36,010 foot-candles.

The intensity actually measured with the foot-candle meter was 35,000 foot-candles. Light intensities were calculated for several other lamp voltages and were compared with the experimental values. The results are shown in Fig. 2. In this graph the lines represent the calculated light intensities, whereas the points were determined experimentally. In view of the low resolving power of the light meter, the agreement is very satisfactory.

*Because foot-candles is most commonly used as a unit of light intensity, it will be used in this report, even though the metric system is employed for all other units.

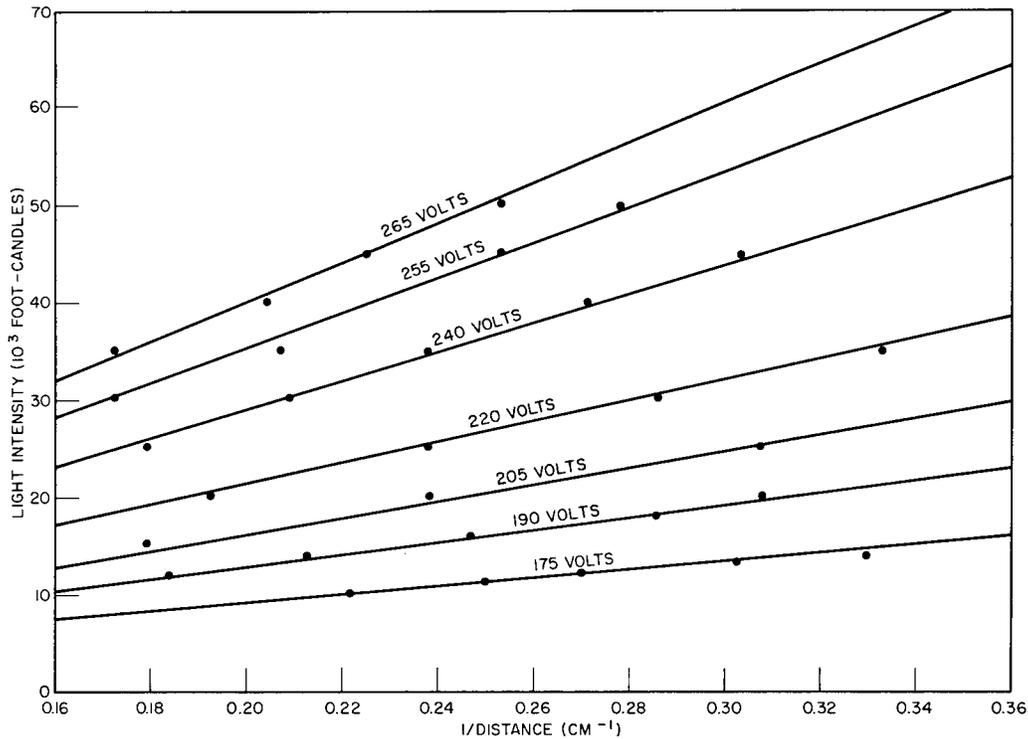


Fig. 2 - Light intensity as a function of distance from lamp at several voltages. The lines indicate the manufacturers statement of luminous output and the points are data from a Weston foot-candle meter

Organism

The Sorokin strain of *Chlorella pyrenoidosa*, 7-11-05, was used in these experiments. This strain has an optimum growth temperature of about 39°C , and was used because of its rapid growth rate. Under optimum conditions its density is doubled in two hours. No attempt was made to maintain the culture bacteria-free.

Culture Medium

To assure an adequate supply of nitrogen, Burk's medium, modified to contain five times the normal amount of urea, was used. The composition of the unmodified medium may be found in Ref. 3. In all the experiments, the culture was diluted with fresh medium at a constant rate of about ten percent of the culture volume per hour.

Cell Concentration

Cell concentrations were estimated with a Klett-Summerson Colorimeter, by comparing the optical density with a standard curve of optical density versus percent wet packed cell volume. The concentrations in these experiments varied from about 0.5 to 1.55 percent packed cell volume. In this concentration range and at the light intensities used, the cultures were light limited and in the linear phase of growth.

General Experimental Procedure

The experiments in this study were made on a daily basis. Cells stored overnight in a refrigerator were put in the culture unit and allowed to grow at constant illumination until the oxygen evolution rate was steady, as shown by the trace on the recorder. This usually required about 45 minutes to an hour. The oxygen production rate was then determined by measuring the gas flow with a wet test meter and by observing the oxygen concentration in the inlet and outlet gas. After the oxygen production determination, the light intensity was changed by varying the lamp voltage, and, when the oxygen concentration in the outlet gas was again steady (about 20 minutes), the oxygen evolution rate was determined. This procedure was repeated for five different culture thicknesses. The results obtained in this manner were not as reproducible as was desired, varying from day to day under apparently identical culture conditions, and the data given in this report actually are the maximum oxygen rates obtained under the stated conditions. However, the reported oxygen rates were all obtained more than once.

RESULTS AND DISCUSSION

Effect of Light Intensity on Oxygen Production at Five Culture Thicknesses

The influence of light intensity on the rate of oxygen production at five culture thicknesses is shown in Fig. 3. Confirming earlier observations, the graph clearly shows that the oxygen evolution rate is a logarithmic function of light intensity in the range of light intensities tested. To see if this relationship was valid throughout the light intensity range of this lamp, the oxygen evolution rate of a culture contained in the 2.2-cm chamber was determined down to zero light intensity. The results, shown in Fig. 4, indicate that oxygen production decreases linearly with the log of the light intensity to about 3000 foot-candles. The marked deviation from linearity at lower light intensities may mean that the respiration rate of the algae in the dark and in the light are different; if the rates were the same, the curve would remain linear down through the compensation point.

As pointed out earlier, the distance from the light source is a variable. However, the 1.0- and 2.2-cm culture chambers were the same distance from the center of the unit, as were the 1.4- and 2.6-cm annuli, so that in these two instances the oxygen productivities can be compared directly. In both of the cases when the illuminated area was the same, the thinner culture annulus produced more oxygen at a given light intensity. Evidently, in this culture unit, the thickness of the culture chamber markedly affects oxygen production even when the illuminated area and light intensity are constant; this contrasts with findings of Tamiya et al. that algal growth rate was independent of culture thickness for a constant light intensity and illuminated area.

The dependence of oxygen production on culture thickness is not easily explained. In the cases when the illuminated area was the same, more oxygen was produced by the smaller culture chamber even though fewer cells were present. For example, the culture in the 1.0-cm chamber produced 190 cc more oxygen per hour than the 2.2-cm culture for a given light intensity even though there were about 18 cc of cells in the 2.2-cm chamber and only about 12 cc of cell in the 1.0-cm chamber. The most obvious explanation for the decrease in the oxygen output is that the rate of respiration was greater in the 2.2-cm culture chamber because more cells were in relative darkness, and this lowered the observed oxygen production. However, in the culture used to obtain the curve in Fig. 4 the dark respiration rate was only 24 cc/hr, equivalent to an oxygen consumption rate of 1.5 cc/hr per cc of cells. Thus it seems that, if the respiration rate in the light and in the dark are the same, the respiration rate has little influence on the change of oxygen production with culture thickness. Subsequent respiration studies at this

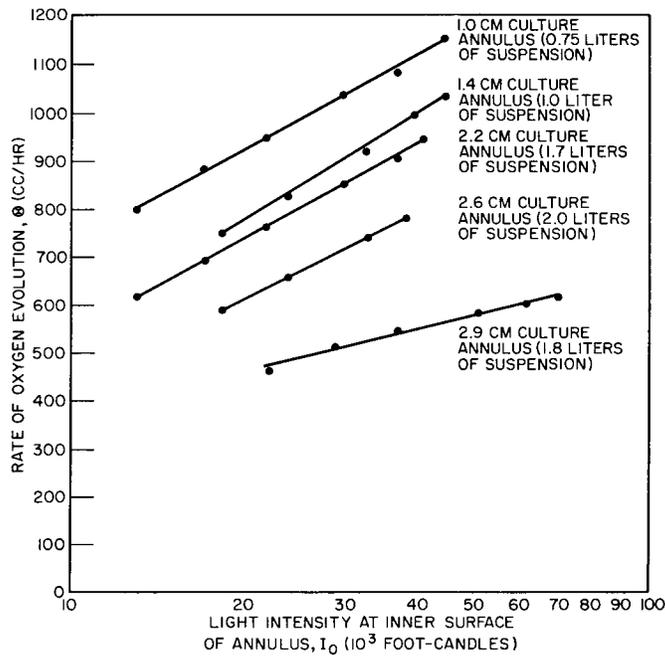


Fig. 3 - Effect of light intensity on oxygen production for five culture thicknesses

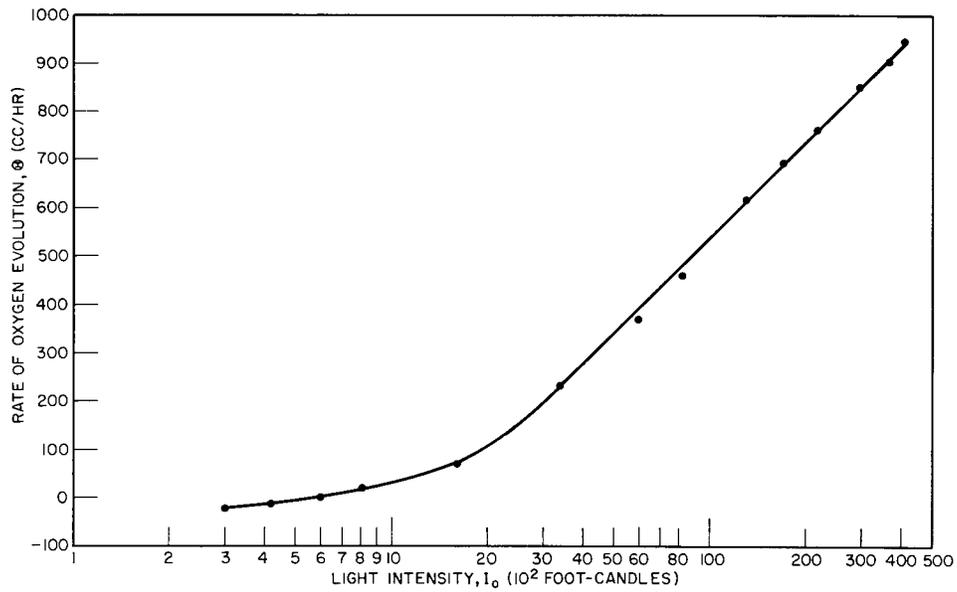


Fig. 4 - Effect of light intensity on oxygen production with a 2.2-cm culture chamber

laboratory have suggested, however, that the respiration rate in the light is much greater than in the dark, being equal to about 10-12 cc/hr per cc of cells. Although respiration is undoubtedly a factor in the relationship between oxygen production and culture thickness, the results of this study do not permit any definite statements to be made at this time concerning its role.

That factors other than respiration affect the change in oxygen production with culture thickness has been shown by the following experiment. A culture was grown at constant illumination in the 1.0-cm culture chamber until the oxygen production was steady at 684 cc/hr. The culture chamber was then changed to 2.2 cm and the original culture was diluted with culture medium and put into this chamber. After the dilution, the oxygen production rate was only 609 cc/hr. Thus, more oxygen was produced by the smaller culture chamber even though the same number of cells were present in both culture chambers and both cultures were in the linear phase of growth. A change in the oxygen production rate between the 1.0-cm and 2.2-cm culture chambers was expected because the amount of light reaching the cells, and therefore the oxygen output per cell, was changed by dilution of the culture. First of all, some of the cells were further from the light source in the 2.2-cm chamber so the average light intensity striking each cell was less, thus lowering the oxygen output of each cell. Opposing this, the mutual shading by the cells was less after the dilution, so more light energy reached each cell, thus raising its oxygen output. Apparently in this experiment the first factor predominated, although it is possible that under different conditions the second factor might become more important and an increase in culture thickness would increase oxygen productivity when the same number of cells are involved.

The highest light intensity used in this study was approximately 69,500 foot-candles, when the 2.9-cm culture chamber was used. Judging from the linearity of the lower curve in Fig. 3, the oxygen production of the culture was not inhibited by too much light at this light intensity. It should be borne in mind, however, that at this light intensity the widest culture chamber was used, and since the suspension was vigorously stirred, it is possible that the culture could tolerate this light intensity only because an individual cell would be exposed to this light intensity for a very short time. Moreover the culture was exposed to this light intensity for only 20 minutes or so, and longer exposures might have had a noticeable effect on the oxygen production.

Oxygen Production per Liter of Suspension as a Function of Culture Thickness

To see if the oxygen production per unit volume of suspension was inversely related to culture thickness as suggested by the findings of Tamiya's group (2), the data from the preceding experiments have been used to calculate the oxygen evolution of a liter of suspension for each of the five culture thicknesses. The results of these calculations are shown in Fig. 5 in which the oxygen production per liter of suspension is plotted against the log of the light intensity as before. Using the data from this plot, it is possible to plot the oxygen production per liter of suspension as a function of culture thickness for a given light intensity. In Fig. 6 the oxygen production per liter of suspension is plotted against the reciprocal of the culture thickness for three light intensities, and it can be seen that the curve for each light intensity is, to a good approximation, a straight line over the experimental range of culture thicknesses and light intensities. This relation may be expressed by the linear equation

$$\frac{\Theta}{V} = \frac{m}{D} + b$$

or

$$\Theta = V \left(\frac{m}{D} + b \right), \quad (4)$$

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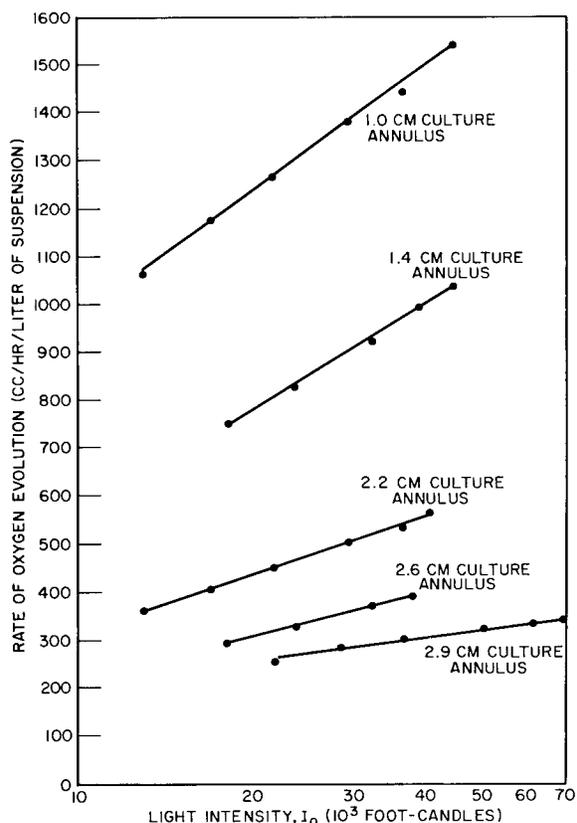


Fig. 5 - Effect of light intensity on oxygen production per liter of suspension for five culture thicknesses

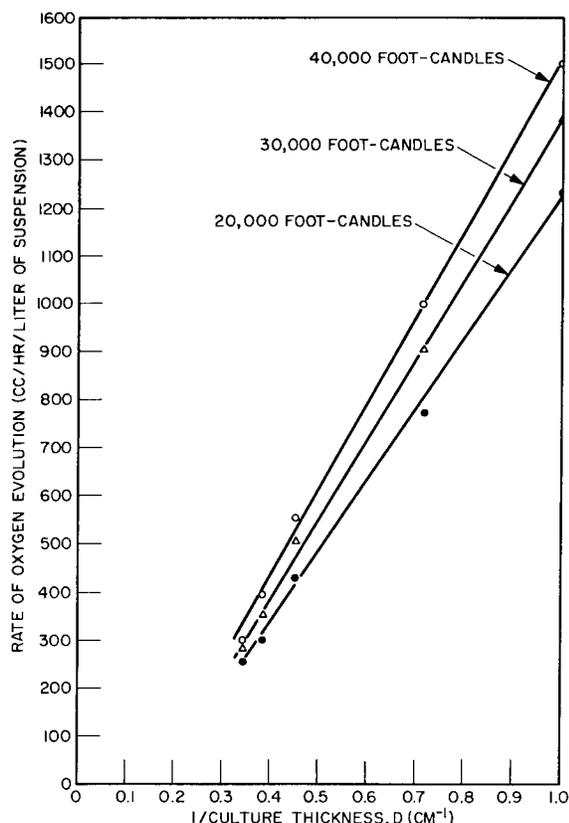


Fig. 6 - Effect of culture thickness on oxygen production

where

Θ = rate of oxygen evolution (cc/hr)

V = suspension volume (liters)

D = culture thickness (cm)

m = slope of line

b = y axis intercept.

The values of the constants m and b depend upon light intensity.

Equation (4) shows how the oxygen yield of this culture unit would be expected to vary with culture thickness and culture volume at a constant light intensity as long as the culture is in the linear phase of growth. This equation would not hold for a thin culture annulus because extremely intense light inhibits algal growth. Thus, a downward change of slope of each of the lines in Fig. 6 would occur at the culture thickness at which too much light begins to inhibit growth and oxygen production.

The inverse relationship between oxygen production per liter of suspension and culture thickness was expected because, for a given suspension volume, the illuminated

area, which is the inner surface of the culture annulus, decreases with culture thickness. In this culture unit the illuminated area per unit volume of suspension, A/V , varies with culture thickness, D , and the distance of the culture annulus from the center of the unit, (called the culture distance in this report), according to

$$A/V = \frac{2r}{D^2 + 2rD} \quad (5)$$

This equation has been used to calculate the illuminated area of a liter of suspension for each of the five experimental culture thicknesses, and the results are shown in Table 1.

Table 1
Calculated Illuminated Areas of One Liter of Suspension
at Five Culture Thicknesses

Culture Thickness D (cm)	Distance of Culture from Light r (cm)	Illuminated Area per Liter of Suspension A/V (cm ² /l)
1.0	4.9	908
1.4	4.5	618
2.2	4.9	371
2.6	4.5	299
2.9	2.9	230

If the oxygen production of the culture unit were determined solely by the extent of the illuminated area, the oxygen evolution rate per liter of suspension would vary with culture thickness in the same way that illuminated area per liter of suspension changes with culture thickness. When the illuminated area per liter of suspension, as shown in Table 1, was plotted against the reciprocal of the culture thickness, the shape of the curve was very similar to those shown in Fig. 6. Since both oxygen production and illuminated area per liter of suspension decreased analogously with culture thickness, it appears that, although culture thickness is a factor, illuminated area is of overriding importance in determining the oxygen production at a constant light intensity.

The dependence of oxygen production on illuminated area in this culture unit can be obtained by rearranging Eq. (5) into

$$V = A \left(\frac{D^2}{2r} + D \right) \quad (6)$$

and substituting this equation into Eq. (4). This gives

$$\Theta = A \left(\frac{D^2}{2r} + D \right) \left(\frac{m}{D} + b \right) \quad (7)$$

Thus, the oxygen production is proportional to illuminated area if the light intensity, culture thickness, and culture distance are all constant.

For present purposes the suspension volume probably is best expressed in terms of the suspension height (h), culture thickness, and distance of the culture from the light source,

$$V = \pi h (D^2 + 2rD), \quad (8)$$

since the suspension height was constant in these experiments while the illuminated area was not. Substituting Eq. (8) into Eq. (4) gives

$$\Theta = \pi h (D^2 + 2rD) \left(\frac{m}{D} + b \right). \quad (9)$$

This equation shows that oxygen production is proportional to the height of the culture annulus also at a constant light intensity, culture thickness, and culture distance.

General Expression Relating Oxygen Production to Light Intensity, Culture Thickness, and Culture Volume

Equation (4) gives the expected variation of oxygen production in this culture unit with culture thickness and culture volume at a constant light intensity. A more useful equation would include the variable of light intensity also. The desired equation could be obtained if the slopes and y intercepts of the lines in Fig. 6 could be evaluated as functions of light intensity since both of these values depend upon the light intensity. Toward this end the slopes of the lines were plotted against the log of the light intensity and a good straight line resulted which obeyed the equation

$$m = 1030 \log I_0 - 2920. \quad (10)$$

Similarly the y axis intercepts were plotted against the log of the light intensity and a line was drawn through the points. The equation of this line was

$$b = -30 \log I_0 - 150. \quad (11)$$

Substitution of Eqs. (10) and (11) into Eq. (5) leads to

$$\Theta = V \left(\frac{1030 \log I_0 - 2920}{D} - 30 \log I_0 - 150 \right). \quad (12)$$

This equation summarizes the experimental observations in this study and gives the expected oxygen yield of this culture unit at a constant light intensity, culture thickness, and culture volume. However, the use of this equation would be justified only under conditions such that the oxygen production falls on, or close to, the lines shown in Figs. 5 and 6. As mentioned earlier, deviations would be expected at small culture thicknesses.

The question arises as to the applicability of Eq. (12) to other units employing the same light source. To answer this question, the equation has been applied to another culture unit in this laboratory. A detailed description of this culture unit may be found in Ref. 3, but essentially it consists of six lamps surrounded by cooling jackets and immersed vertically in a suspension contained in a large glass cylinder. Although the light sources are arranged symmetrically in this unit, the light path (culture thickness) varied from about 1.6 to 4.5 cm. The average culture thickness was estimated, however, with the use of Eq. (8) since the suspension volume, suspension height, and distance of the culture from the light source were all known. The culture thickness was calculated as 2.1 cm and was then substituted into Eq. (12) with the appropriate values for the volume of suspension and the light intensities obtained with five lamp voltages. The light intensities were not measured experimentally but were calculated on the basis of the lumen output of the lamp by the method described in the Experimentation section. A comparison of the calculated and experimental oxygen production rates is shown in Fig. 7.

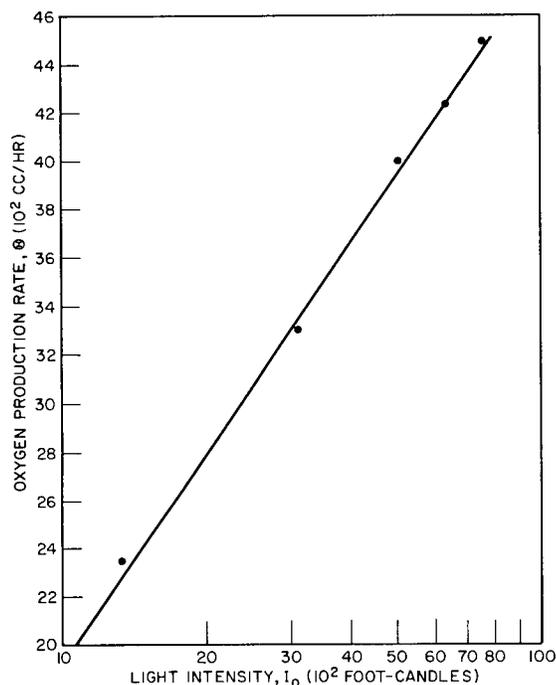


Fig. 7 - Comparison of experimental and calculated oxygen production rates for a six-light culture unit. The line indicates rates calculated according to Eq. (12), while the points indicate observed rates.

The excellent agreement between the observed and calculated oxygen production rates suggests that Eq. (12) is not strictly limited to a particular culture unit, but may be applicable over a wide range of experimental conditions. Thus it is possible to reach some conclusions about the oxygen yield expected from a cylindrical culture unit at a certain light intensity, culture thickness, and culture volume before any laboratory work is done. Since one equation can be used to predict reliably the oxygen outputs of two culture units differing so much in geometry and manner of illumination, it is possible that equations of the same form as Eq. (12) may be derived for other culture-unit configurations and light sources.

The observation that the oxygen production of both the culture units depends upon light intensity and culture thickness in the same way is not too surprising, since the two relationships which form the basis of Eq. (12), the inverse relationship between oxygen rate and culture thickness and the logarithmic relationship between oxygen rate and light intensity, have been qualitatively supported by the algal growth studies of Tamiya and his group (2).

Oxygen Production at a Constant Lamp Voltage

If the voltage of the lamp is kept constant, Eq. (2), which relates light intensity and distance, can be incorporated into Eq. (12). For this purpose, Eq. (2) is put into the logarithmic form

$$\log I_0 = \log k - \log r. \quad (13)$$

Substituting this equation into Eq. (12) gives

$$\Theta = V \left[\frac{1030 (\log k - \log r) - 2920}{D} - 30 (\log k - \log r) - 150 \right]. \quad (14)$$

For reasons to be given later, it is better to substitute the value of V as given by Eq. (8) into the above equation, giving

$$\Theta = \pi h (D^2 + 2rD) \left[\frac{1030 (\log k - \log r) - 2920}{D} - 30 (\log k - \log r) - 150 \right]. \quad (15)$$

The term within the brackets gives the expected oxygen output of a liter of suspension; the rest of the right side of the equation represents the volume of suspension. Since h and r are usually given in centimeters, the last term should be changed, so that it gives the oxygen yield of a cubic centimeter of suspension. This is done by dividing the constants within the brackets by 1000, giving

$$\Theta = \pi h (D^2 + 2rD) \left[\frac{1.03 (\log k - \log r) - 2.92}{D} - 0.03 (\log k - \log r) - 0.15 \right]. \quad (16)$$

Since h (the height of the lamp) is a constant for this unit and since k can be readily obtained by graphical means for a given lamp voltage, this equation allows an estimate to be made of the oxygen output, solely from a knowledge of the culture thickness and culture distance.

At 265 volts, the highest voltage possible with the variable transformer used, $\log k$ equals 5.30. Inserting this value into Eq. (16) we get

$$\begin{aligned} \Theta &= \pi h (D^2 + 2rD) \left[\frac{1.03 (5.30 - \log r) - 2.92}{D} - 0.03 (5.30 - \log r) - 0.15 \right] \\ &= \pi h (D^2 + 2rD) \left[\frac{2.54 - 1.03 \log r}{D} + 0.03 \log r - 0.3 \right]. \end{aligned} \quad (17)$$

Equation (17) is based on the highest possible voltage so the oxygen production given by this equation should be the maximum obtainable at a given D and r , assuming that light is the only factor limiting growth. Hence, the problem of calculating the maximum oxygen yield for this culture unit reduces to the question "What is the culture thickness and how far should the culture be from the light source?" In principle this question could be answered by maximizing the oxygen production, as determined by Eq. (17), with respect to each of the two variables D and r . Unfortunately the equations do not have mathematical maxima.

Oxygen Production as a Function of Culture Thickness

As already pointed out, the effect of culture thickness on oxygen production in this culture unit could not be determined directly from the experiment because not all the culture annuli were the same distance from the center of the unit, and the oxygen output of a certain culture annulus depends upon its position in the culture unit. However, with Eq. (16) available, it is now possible to show this relationship since the equation shows that for a fixed annular chamber exposed to constant illumination (constant k , h , and r) the oxygen production is determined by culture thickness alone.

The curves in Fig. 8 show how the oxygen production would be expected to vary with culture thickness in this culture unit at three culture distances at full lamp voltage according to Eq. (17). The culture distances are approximately within the experimental range of culture thicknesses so Eq. (17) can be used to accurately predict the oxygen production rates for these culture distances. At each distance the graph shows that an increase in culture thickness decreases oxygen production, the effect being more pronounced the farther the culture is from the center of the unit. Although the effect of culture thickness on oxygen production undoubtedly would change with light intensity, the advantage of using a small culture thickness is obvious, especially if the culture is to be placed relatively far from the light source.

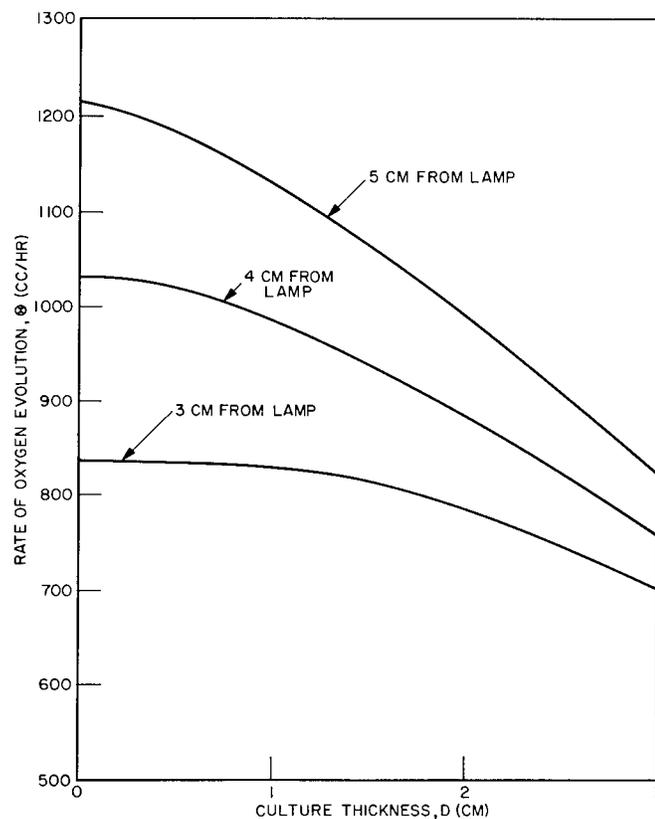


Fig. 8 - Effect of culture thickness on oxygen production at three culture distances according to Eq. (17)

Oxygen Production as a Function of Culture Distance

Just as Eq. (17) was used to estimate the change of oxygen production with culture thickness at a constant culture distance and at full lamp voltage, it can also be used to show how the oxygen production of a fixed culture annulus would be expected to change with culture distance at full lamp voltage. In Fig. 9 the oxygen production rate calculated by Eq. (17) is shown as a function of culture distance for three culture thicknesses which essentially fall within the experimental range. The increase in oxygen production with culture distance shows that, for the culture distances considered, the increase in culture volume and illuminated area with distance is much more important in determining oxygen

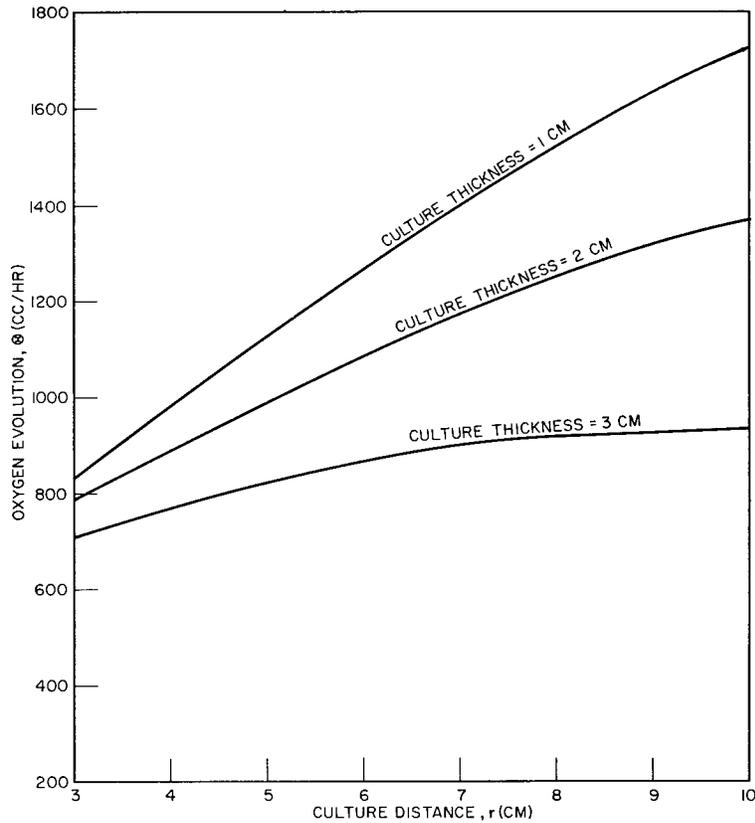


Fig. 9 - Effect of culture distance on oxygen production for three culture thicknesses according to Eq. (17)

production than is the decrease in light intensity with distance. It is likely, however, that at some distance light intensity predominates, so that an increase in culture distance would decrease oxygen production. This distance is so great, however, that it probably has no practical significance.

Oxygen Production and Power Input

In an effort to determine the relationship between oxygen production and power input, the rate of oxygen production for the five culture thicknesses was plotted first as a function of the lamp voltage required to give the light intensities shown in Fig. 3. The rate of oxygen evolution for each culture thickness was found to be linearly related to the voltage. Since power is proportional to the square of the voltage, the rate of oxygen evolution should be a square-root function of the wattage consumed by the lamp. In accord with theory, Fig. 10 shows that the rate of oxygen evolution varies linearly with the square root of wattage. This plot shows the relationship between oxygen production and electrical power for a fixed culture chamber; it does not show how oxygen production changes with culture thickness because this could be determined only if each culture chamber was the same distance from the center of the unit, a condition not realized in these experiments.

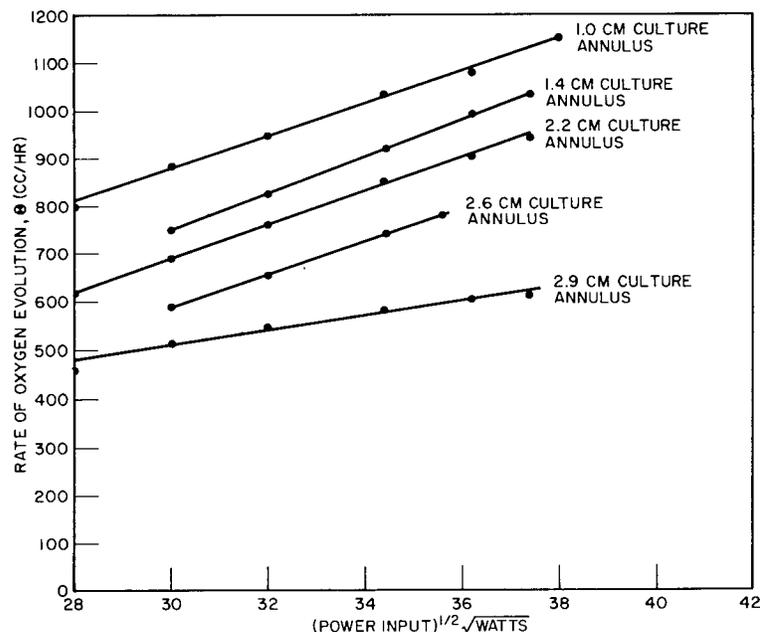


Fig. 10 - Oxygen production and power input for five culture thicknesses

Culture Unit Efficiency

The percentage conversion of electrical energy to chemical energy and of light energy to chemical energy have been calculated for the 1.0- and 2.2-cm culture chambers at several power inputs; the results are shown in Table 2. The energy output of the unit was calculated on the assumption that the chemical bond energy of a mole of oxygen is 110 kilocalories, or 4800 calories per liter of oxygen. The lamp efficiencies were estimated from data furnished by the lamp manufacturer, and the oxygen production rates have been corrected to standard temperature and pressure.

The results show that for both culture thicknesses, the maximum conversion of electrical to chemical energy occurred at a power input of 900 watts, although the lamp was most efficient in converting electrical to visible light energy at 1520 watts. Therefore, based on these figures, if the most oxygen is desired for the least amount of power, about 205 volts should be applied to the light source.

The efficiency of photosynthesis in these experiments (last column) is seen to decrease with wattage input for both culture thicknesses. This decrease probably results mainly from a greater loss of light energy penetrating through the culture at the higher wattages. Although there is not general agreement on the point, the efficiency of photosynthesis is considered to be around 20% under optimum conditions of growth when almost all of the light is absorbed by the cells and when monochromatic light is used at the wavelength at which the cells are able to utilize the light energy most effectively. Thus the maximum efficiency of the conversion of electrical energy to chemical energy at say 900 watts using this light source would be

$$(\text{lamp efficiency}) \times (\text{photosynthesis efficiency}) = 5.8\% \text{ of } 20\% = 1.16\%$$

or about 1.2% conversion of electrical energy to chemical energy. Hence the 0.51% conversion obtained experimentally is not unreasonable, since some of the light penetrated

Table 2
Electrical Efficiency of Culture Unit for Two Culture Thicknesses

Volts	Watts	Lamp Efficiency, Electrical to Visible Light Energy (%)	Oxygen Output (cc/hr)	Energy Conversion (%)	
				Electrical to Chemical	Light to Chemical
1.0-cm Culture Thickness					
190	846	5.0	740	0.49	9.8
205	900	5.8	825	0.51	8.8
220	1023	6.6	885	0.48	7.4
240	1225	7.8	965	0.44	5.6
255	1370	8.7	1005	0.41	4.7
265	1520	9.3	1076	0.39	4.2
2.2-cm Culture Thickness					
125	441	2.3	217	0.28	12.1
150	581	3.1	346	0.33	10.7
175	740	4.3	441	0.33	7.7
190	846	5.0	575	0.38	7.6
205	900	5.8	646	0.40	6.9
220	1023	6.6	710	0.39	5.9
240	1225	7.8	794	0.36	4.6
255	1370	8.7	844	0.34	4.0
265	1520	9.3	882	0.32	3.5

the culture and was lost to the atmosphere, and since the light source emits light over the entire range of the visible spectrum. Moreover the oxygen evolution rates were not corrected for respiration, so that the true electrical efficiency of the system is higher than that observed.

Estimated Space and Power Requirements for 1-Man Unit

Since the most oxygen was produced by the culture unit when the 1.0-cm culture chamber was used, the space and electrical power requirements of a photosynthetic gas exchanger capable of providing the oxygen needs of one man have been calculated on the basis of this culture thickness. The results of these calculations are shown in Table 3. In arriving at the space and power requirements, it was assumed that one man consumes 25 liters of oxygen per hour (STP).

The estimated volume and power requirements may be compared with those of a Treadwell electrolytic oxygen generator currently being used in some nuclear submarines. This generator, capable of providing oxygen for a 100-man crew, occupies 175 cubic feet of space and operates at 75 kilowatts. Table 3 shows that the space required for a 100-man algal unit would be competitive with that required by the Treadwell

generator, but the power demands of the algal unit would be about forty times greater. In view of the dependence of oxygen production on culture thickness, the most obvious way to reduce the power and space requirements would be to use a lesser culture thickness, but there is a practicable minimum. Even in the simple cylindrical culture model used in this study, there was not sufficient agitation of the suspension in the 1-cm culture chamber to prevent sticking of the cells on the wall of the container after several days culture.

Table 3
Estimate of Electrical Power and Space
Requirements of 1-Man Unit

Experimental Results		Estimate of Re- quirements of 1-Man Unit	
Watts	Oxygen Output (cc/hr) (STP)	Volume* (ft ³)	Power (kw)
846	740	2.69	29
900	825	2.58	27
1023	885	2.41	29
1225	965	2.19	32
1370	1005	2.11	34
1520	1076	1.98	35

*Volume includes culture volume and cooling space between light source and culture but does not include auxiliary equipment such as stirring motors, blowers, and heat exchangers.

The power requirements at each wattage could be reduced also by moving the culture chamber outward from the light source, thereby increasing the illuminated area and suspension volume, but this would raise the space requirements. An approach to reduce the power requirements without increasing the space requirements would be to devise a culture unit with a high illuminated area/space ratio. As an illustration, the illuminated area of the present unit would be greatly increased if the light source were encased in a tubular structure with transparent fins extending from the sides so that light would be transmitted through the fins. By sending the suspension between the fins, the cells would effectively be illuminated from three sides instead of one as in the present unit. In such a finned-tube culture unit, the light would be spread out over a wider area, thereby increasing the illuminated area but not the space required for the unit, and even though the light intensity per unit illuminated area would be less in the finned-tube structure than in the straight tubular culture unit, its oxygen production undoubtedly would be much greater under comparable conditions because of the greater extent of the illuminated area. Once again, however, the sticking tendency of the cells might be a problem.

SUMMARY

1. The oxygen production of cultures in the linear phase of growth has been found to be a logarithmic function of light intensity except at relatively low light intensities.

2. The oxygen production per liter of suspension has been found to be linearly related to the reciprocal of culture thickness in the experimental range of culture thicknesses and light intensities.

3. From the above two relationships, an empirical equation has been derived showing the variation of oxygen production with light intensity, culture thickness, and culture volume. This equation has been found to apply equally well to two culture units differing widely in design, suggesting that the equation may have wide applicability.

4. The maximum conversion of the electrical energy to chemical energy based on oxygen evolution was 0.51 percent in this culture unit. The maximum conversion of visible light energy to chemical energy, the photosynthetic efficiency, was about 12 percent.

5. From the results obtained in this study, a photosynthetic gas exchanger capable of providing the oxygen needs of one man would occupy about 2 cubic feet and would consume about 30 kilowatts of power.

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13. ABSTRACT <p>Data from a small cylindrical culture unit with variable annular culture chambers indicate that: (a) the rate of oxygen evolution by an algal culture in the linear phase of growth is a logarithmic function of light intensity, and (b) the rate of oxygen evolution per unit volume of suspension is linearly related to the reciprocal of culture thickness. These two relationships have been combined in an empirical equation, which gives the expected variation of the oxygen production rate with light intensity, culture thickness, and suspension volume. The applicability of this equation has been tested on a larger, multi-light culture unit in this laboratory. The agreement between the experimental and calculated oxygen production rates was very satisfactory, suggesting that the equation is not limited to a particular culture unit but may have wide applicability.</p> <p>The efficiency of the culture unit from the viewpoint of electrical power utilization has been calculated, and it was found that the maximum conversion of electrical energy to chemical energy based on oxygen evolution was only 0.51 percent. The maximum efficiency in converting light energy to chemical energy was approximately 12 percent.</p> <p>An extrapolation of the experimental results suggests that approximately 2 cubic feet and 30 kilowatts would be required to provide for the oxygen needs of one man.</p>		

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Algae - applications						
Oxygen production						
Light intensity						
Culture thickness						

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