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

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Data from a small cylindrical culture unit with variable annular culture chambers indicate that (i) the rate of oxygen evolution by an algal culture in the linear phase of growth is a logarithmic function of light intensity, and (ii) 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, multilight 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 standpoint of oxygen output (chemical energy) relative to electrical energy to supply the light source has been calculated, and the maximum value of 0.51% was obtained. The energy to run auxiliary equipment was not a factor in these calculations. The maximum efficiency in converting light energy to chemical energy was approximately 12%. An extrapolation of the experimental results suggests that approximately 2 ft³ and 30 kw would be required to provide the oxygen needs of one man.

To determine the feasibility of an algal system for providing oxygen and absorbing carbon dioxide in an enclosed environment, such as a space vehicle or a nuclear-powered submarine, 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, among which the most important ones are the intensity of the incident light, the distance the light must penetrate through the culture (the culture thickness), and the illuminated area. In addition, the oxygen production rate should be highest at a given light intensity only when the culture is in the linear phase of growth, for that is when the algal growth rate is at a maximum. Consequently, only cultures in this phase of growth were used in this study, and it is instructive to consider the factors which affect oxygen production under these conditions.

If it is assumed that light is the only factor limiting algal growth and that the oxygen evolution rate parallels growth, the oxygen production of a culture in the phase of linear growth should be dependent only on the oxygen output per cell and the number of cells (4). Thus, as a culture grows, an increasing number of cells shade each other, thereby decreasing the amount of light energy reaching each cell and reducing the oxygen output per cell. However, the resulting decrease in the oxygen output of each cell is compensated by an increase in the number of cells producing oxygen. Since the growth rate and consequently the oxygen production rate are constant in the region of linear growth, the product of the two opposing factors controlling growth and oxygen production, i.e., the oxygen output per cell and the number of cells, must also be constant as long as the culture remains in the linear phase of growth.

In agreement with algal growth kinetics, it was found earlier (4) that for cultures which contained 0.5 to 1.0% of cells and which were in the linear phase of growth, the oxygen production rate was the same, within experimental error, for each cell density at a given light intensity. Since the cell concentrations used in the present work were approximately in the same range as that used earlier, cell concentration was not considered to be an important factor in determining the oxygen production rates of cultures used in this study.

The effect of light intensity on the rate of oxygen evolution by cultures in the linear phase of growth has been studied previously (4); oxygen production increased logarithmically with light.
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. 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 (Fig. 1). 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, Hamden, Conn., 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 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

FIG. 1. Schematic diagram of culture unit.
through a drying column into an infrared carbon dioxide analyzer (Mine Safety Appliances Co., Pittsburgh, Pa., model 300) and a paramagnetic oxygen analyzer (Beckman Instruments, Inc., Fullerton, Calif., 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 1 liter/min, 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 otherwise, all gas volumes are reported for room temperature and pressure.

**Light source.** A G.E. incandescent lamp (model 1500 T3Q/Cfl) served as the light source (1,500 W 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 foot-candle meter (Weston Instruments, Inc., Newark, N.J., model 614) with the use of neutral density filters. The available culture annuli were located 2.9, 4.5, and 4.9 cm from the lamp, so that 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 \( r \).

\[
A = 2\pi rh \quad (1)
\]

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 (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. (Because foot-candles is most commonly used as a unit of light intensity, it will be used in this paper, even though the metric system is employed for all other units.) 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, luminous can be easily converted into foot-candles by the formula lumens/ft² = foot-candles. Since the lamp was 0.705 ft high and the illuminated area varies with distance \( r \) according to equation 1,

\[
A = 2\pi rh = (6.28)(0.705)r = 4.43 \, r \, \text{ft}^2 \quad (3)
\]

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 equation 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 ft-c.

The intensity actually measured with the foot-candle meter was 35,000 ft-c. Light intensities were calculated for several other lamp voltages and were compared with the experimental values (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.

**Organism.** The Sorokin strain of *Chlorella pyrenoidosa*, 7-11-05, was used in these experiments. This strain has an optimal growth temperature of about 39 C, and was used because of its rapid growth rate. Under optimal conditions, its density is doubled in 2 hr. No attempt was made to maintain the culture bacteria free.

**Culture medium.** To assure an adequate supply of nitrogen, Burk's medium (2), modified to contain five times the normal amount of urea, was used. In all the experiments, the culture was diluted with fresh medium at a constant rate of about 10% 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 per cent of cell volume (wet packed). The concentrations in these experiments varied from about 0.5 to 1.55% of 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 carried out daily. Cells stored overnight in a refrigerator were transferred to the culture unit and allowed to grow at constant illumination until the
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Fig. 3. Effect of light intensity on oxygen production for five culture thicknesses.

Oxygen evolution rate was steady, as shown by the trace on the recorder. This usually required about 45 min to 1 hr. 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 min), 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 as much as 7% from day to day under apparently identical culture conditions. The data given in this report are the maximum oxygen rates obtained under the stated conditions.

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. The graph confirms earlier observations and clearly shows that the oxygen evolution rate is a logarithmic function of light intensity in the range of light intensities tested. To determine whether 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 (Fig. 4) indicate that oxygen production decreases linearly with the log of the light intensity to about 3,000 ft-c. 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 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. (5) 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 cm³ more oxygen per hr than did the 2.2-cm culture for a given light intensity, even though there were about 18 cm³ of cells in the 2.2 cm chamber and only about 12 cm³ of cells 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 cm³/hr, equivalent to an oxygen consumption rate of 1.5 cm³/hr per cm³ of cells. Thus, it seems that the respiration rate has little influence on the change of oxygen production with culture thickness if the respiration rate in the light and in the dark are the same. Subsequent respiration studies at this laboratory have sug-
gested, however, that the respiration rate in the light is much greater than in the dark, being equal to about 10 to 12 cm$^3$/hr per cm$^2$ 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 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 cm$^3$/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. To keep the cell concentration from increasing significantly, the oxygen production rate was determined several minutes after the light had been turned on and was only about 609 cm$^3$/hr. Thus, more oxygen was produced by the smaller culture chamber even though the same number of cells was 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- 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 farther from the light source in the 2.2-cm chamber so that 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 that 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 is involved.

Because of the nature of the above experiment, it was necessary to make a choice in the timing of the determination of the oxygen output of the culture in the larger chamber. Inasmuch as the oxygen output was measured soon after the light was turned on, the reading might have been taken before the metabolism of the algal cells had adapted to the new environment and, therefore, before photosynthesis had reached a constant rate. On the other hand, if the culture had been allowed to grow for too long, there would have been appreciably more cells in the 2.2-cm chamber than were present in the 1.0-cm chamber, thereby vitiating the purpose of the experiment. Therefore, a compromise was made in choosing when to determine the oxygen output. The observed oxygen evolution rate of about 609 cm$^3$/hr of the culture in the 2.2-cm chamber was somewhat higher than the average rate observed in later experiments; therefore, it seems reasonable to assume that if sufficient time had been allowed for photosynthesis to reach a steady state, the oxygen production rate would have been less.

**Oxygen production per liter of suspension as a function of culture thickness.** To determine whether the oxygen production per unit volume of suspension was inversely related to culture thickness, as suggested by the findings of Tamiya’s group (5), 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

![Fig. 5. Effect of light intensity on oxygen production per liter of suspension for five culture thicknesses.](image-url)
good approximation, a straight line over the experimental range of culture thicknesses and light intensities. This relation may be expressed by the linear equation

\[ \Theta = \frac{m}{D} + b \quad \text{or} \quad \Theta = V \left( \frac{m}{D} + b \right), \]  

where \( \Theta \) = rate of oxygen evolution (cm\(^3\)/hr), \( V \) = suspension volume (liters), \( D \) = culture thickness (cm), \( m \) = slope of line, and \( b \) = \( y \) 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), by the equation

\[ A/V = \frac{2r}{D^2 + 2rD} \]  

(5)

This equation has been used to calculate the illuminated area of 1 liter of suspension for each of the five experimental culture thicknesses (Table 1).

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 (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 equation 5 into

\[ V = A \left( \frac{D^2}{2r} + D \right) \]  

(6)

and substituting this equation into equation 4. This gives

\[ \Theta = A \left( \frac{D^2}{2r} + D \right) \left( \frac{m}{D} + b \right) \]  

(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,

\[
V = \pi h (D^2 + 2rD) \tag{8}
\]

since the suspension height was constant in these experiments, whereas the illuminated area was not. Substituting equation 8 into equation 4 gives

\[
\Theta = \pi h (D^2 + 2rD) \left( \frac{m}{D} + b \right) \tag{9}
\]

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 also include the variable of light intensity. 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

\[
m = 1,030 \log I_0 - 2,920 \tag{10}
\]

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

\[
b = -30 \log I_0 - 150 \tag{11}
\]

Substitution of equations 10 and 11 into equation 5 leads to

\[
\Theta = V \left( \frac{1,030 \log I_0 - 2,920}{D} \right. \\
\left. - 30 \log I_0 - 150 \right) \tag{12}
\]

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 Fig. 5 and 6. As mentioned earlier, deviations would be expected at small culture thicknesses.

The question arises as to the applicability of equation 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 a previous paper (2). 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 equation 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 equation 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 earlier.

A comparison of the calculated and experimental oxygen production rates is shown in Fig. 7.

The excellent agreement between the observed

![Graph](https://example.com/graph.png)

**Fig. 7.** Comparison of experimental and calculated oxygen production rates for a six-light culture unit. The line indicates rates calculated by equation 12; the points indicate observed rates.
and calculated oxygen production rates suggests that equation 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 equation 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 equation 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 et al. (5).

Oxygen production at a constant lamp voltage.

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

\[ \log I_o = \log k - \log r \]

(13)

Substituting this equation into equation 12 gives

\[
\Theta = V \left[ \frac{1.03 (\log k - \log r) - 2.92}{D} \right. \\
\left. - 30 (\log k - \log r) - 150 \right]
\]

(14)

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

\[
\Theta = \pi h(D^2 + 2rD) \\
\cdot \left[ \frac{1.03 (\log k - \log r) - 2.92}{D} \right. \\
\left. - 30 (\log k - \log r) - 150 \right]
\]

(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 1,000, giving

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

(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 V, the highest voltage possible with the variable transformer used, \( \log k \) equals 5.30. Inserting this value into equation 16, we get

\[
\Theta = \pi h(D^2 + 2rD) \\
\cdot \left[ \frac{1.03(5.30 - \log r) - 2.92}{D} \right. \\
\left. - 0.03(5.30 - \log r) - 0.15 \right]
\]

(17)

\[
\Theta = \pi h(D^2 + 2rD) \\
\cdot \left[ \frac{2.54 - 1.03 \log r}{D} + 0.03 \log r - 0.3 \right]
\]

(18)

**Fig. 8.** Effect of culture thickness on oxygen production at three culture distances, calculated by equation 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 equation 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 equation 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 equation 17. The culture distances are approximately within the experimental range of culture thicknesses, so equation 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.

**Oxygen production as a function of culture distance.** Just as equation 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 equation 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 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...
| Voltage | Wattage | Per cent lamp efficiency, electrical to visible light energy | Oxygen output (cm²/hr) | Per cent energy conversion |
|---------|---------|----------------------------------------------------------|------------------------|---------------------------|
|         |         | Electric to chemical | Light to chemical     |                          |
| 190     | 846     | 5.0               | 740          | 0.49                     | 9.8                       |
| 205     | 900     | 5.8               | 825          | 0.51                     | 8.8                       |
| 220     | 1,023   | 6.6               | 885          | 0.48                     | 7.4                       |
| 240     | 1,225   | 7.8               | 965          | 0.44                     | 5.6                       |
| 255     | 1,370   | 8.7               | 1,005        | 0.41                     | 4.7                       |
| 265     | 1,520   | 9.3               | 1,076        | 0.39                     | 4.2                       |

**Culture thickness 2.2 cm**

| Voltage | Wattage | Per cent lamp efficiency, electrical to visible light energy | Oxygen output (cm²/hr) | Per cent energy conversion |
|---------|---------|----------------------------------------------------------|------------------------|---------------------------|
|         |         | Electric to chemical | Light to chemical     |                          |
| 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     | 1,023   | 6.6               | 710          | 0.39                     | 5.9                       |
| 240     | 1,225   | 7.8               | 794          | 0.36                     | 4.6                       |
| 255     | 1,370   | 8.7               | 844          | 0.34                     | 4.0                       |
| 265     | 1,520   | 9.3               | 882          | 0.32                     | 3.5                       |

The results show that for both culture thicknesses, the maximum conversion of electrical to chemical energy occurred at a power input of 900 w, although the lamp was most efficient in converting electrical to visible light energy at 1,520 w. Therefore, based on these figures, if the most oxygen is desired for the least amount of power, about 205 v should be applied to the light source.

The efficiency of photosynthesis in these experiments (Table 2, 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 optimal 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 w with this light source would be: (lamp efficiency) \times (photosynthesis efficiency) = 5.8\% \times 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 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.

**Table 3. Estimate of electrical power and space requirements for one-man unit**

| Experimental results | Estimate of requirements for one-man unit\(^a\) |
|----------------------|-----------------------------------------------|
| Wattage | Oxygen output\(^b\) | Volume | Power |
|---------|---------------------|--------|-------|
| 846     | 740                 | 2.69   | 29    |
| 900     | 825                 | 2.58   | 27    |
| 1,023   | 885                 | 2.41   | 29    |
| 1,225   | 965                 | 2.19   | 32    |
| 1,370   | 1,005               | 2.11   | 34    |
| 1,520   | 1,076               | 1.98   | 35    |

\(^a\) Volume includes culture volume and cooling space between light source and culture, and power refers to energy for illumination only. Volume and electrical power for auxiliary equipment such as stirring motors, blowers, and heat exchangers are not considered in these estimates.

\(^b\) Expressed as cubic centimeters per hour at standard temperature and pressure.
Estimated space and power requirements for a one-man unit. Since most of the 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 (Table 3). In arriving at the space and power requirements, it was assumed that one man consumes 25 liters of oxygen per hr at standard temperature and pressure (1).

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.

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