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PHOTOSYNTHESIS IN SEWAGE TREATMENT

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SYNOPSIS

The stabilization of organic matter in sewage wastes requires oxygen, which in secondary treatment plants is normally obtained from the atmosphere. The primary source of atmospheric oxygen is photosynthesis, for which the sun supplies the energy and water supplies the oxygen. Sewage contains the necessary nutrients for photosynthetic organisms to produce oxygen and at the same time to fix these valuable nutrients as well as solar energy in reclaimable material. Laboratory and pilot-plant investigations of sewage treatment in open ponds by photosynthetically produced oxygen have been conducted during the years 1951–1955. These studies have provided some basic principles which can be utilized for the engineering design of the process as well as for the prediction of the operational performance of new or existing oxidation ponds. In this paper the authors have formulated design criteria based on these principles. The chemical, biological, operational, and economic factors that affect the use of engineered photosynthesis as a method for producing oxygen and reclaimable wastes are outlined.

INTRODUCTION

The impounding of domestic sewage and industrial wastes in natural and artificial ponds has been practiced under various circumstances for a long time. In recent years, however, descriptions of pond designs and structures have appeared in engineering literature with increasing frequency, indicating that impounding is emerging as a distinct treatment process. Such facilities have been most commonly called "sewage lagoons" and "industrial waste lagoons."

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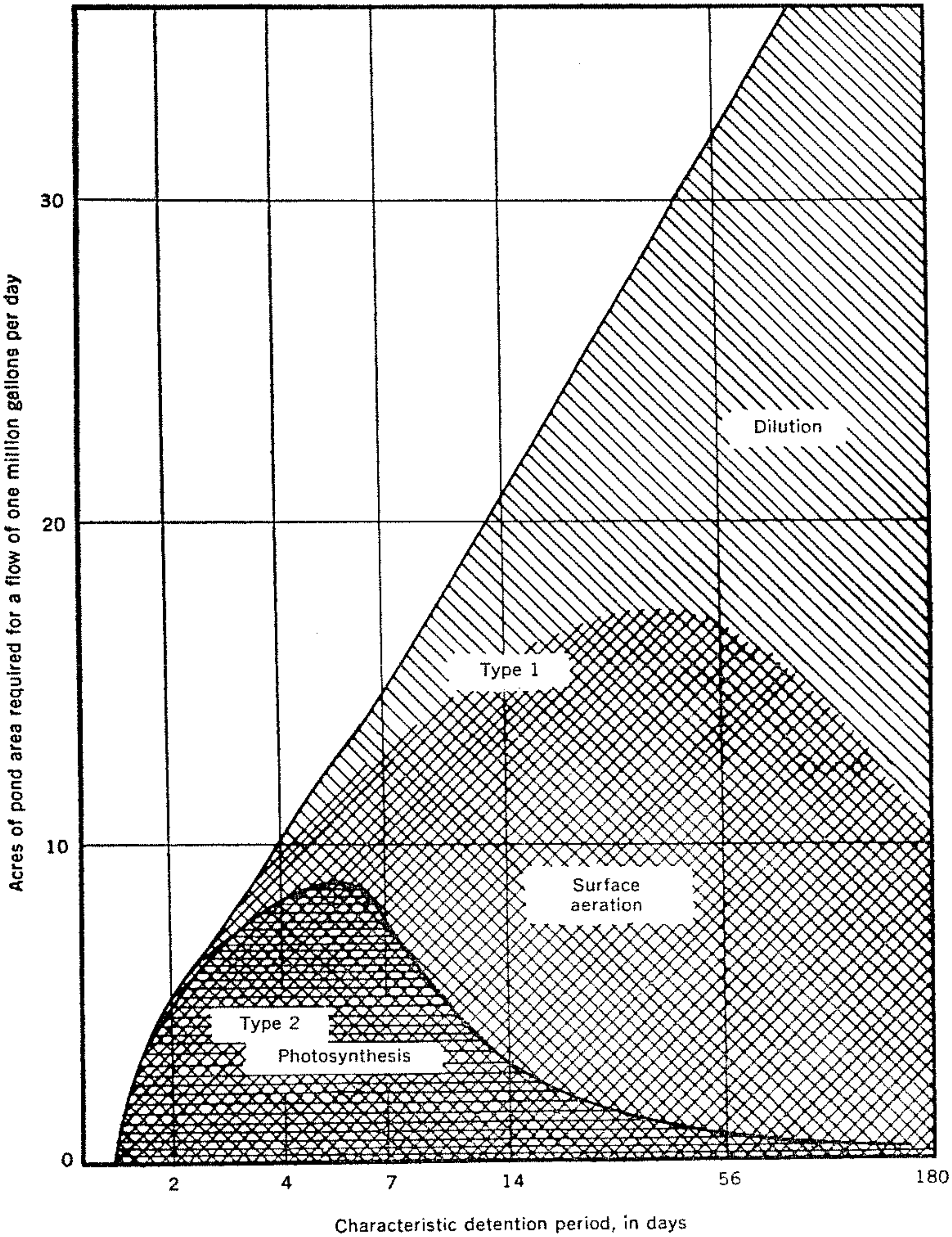

FIG. 1.—GENERAL TYPES OF OXIDATION PONDS—SCHEMATIC REPRESENTATION

Those more subject to engineering analysis are often termed "oxidation ponds." Lagoons or ponds have been used as holding reservoirs for partly treated effluents from overloaded treatment plants and as leaching reservoirs for percolating liquid wastes into the soil; they have also been used in either primary or secondary sewage treatment, or in both. Ponds of this kind have certain characteristics in common: They accomplish a degree of treatment by biological oxidation, and they may produce growths of photosynthetic organisms, principally green algae.

Oxidation-Pond Types.—Studies indicate that oxidation ponds which differ greatly in detention time or physical size may also differ greatly in the principal mechanism by which oxygen is supplied to newly introduced wastes. For a fixed rate of inflow to ponds of various relative sizes and detention periods, the two principal mechanisms and corresponding pond types may be shown schematically as in Fig. 1.

In oxidation ponds of Type 1, having detention periods ranging from three weeks to six months or more, surface aeration is the most important source of oxygen. The larger units of this type which furnish oxygen by dilution are comparable to natural lakes because their physical size is so great that they may receive wastes with little depletion of their oxygen reserves. The design of such units has been described recently by W. Van Heuvelen and Jerome H. Svore.[3]

The smaller Type 1 oxidation ponds are commonly designed for detention periods of from three weeks to six weeks. They depend principally on surface reaeration with atmospheric oxygen which is accelerated by partial depletion of their oxygen reserve as oxidation of organic matter progresses. The design of this type of pond has been described by D. H. Caldwell,[4] A.M. ASCE.

Type 2 ponds utilize detention periods of less than one week. Their small size makes them highly dependent on the biological process of photosynthesis to yield the oxygen needed for oxidizing the entering wastes. This type of pond has not previously been described in the literature and thus far has been built only on a pilot scale.

As indicated in Fig. 1, no sharp distinctions are made between the pond types because there is overlapping in their oxygenation mechanisms. Photosynthesis, the major source of oxygen in ponds of Type 2, may also contribute to the oxygen resources of ponds of Type 1 whenever conditions are favorable for vigorous algal growth and also where recirculation is used. Surface aeration is a source of oxygen for ponds of Type 2, especially at night when photosynthetic oxygen production is nonexistent.

The principles of waste treatment by dilution and, to some degree, by surface aeration have been described in the engineering literature.[5,6] Few practical data on the principles of waste treatment by engineered photosynthesis are available however. It is the purpose of this paper to present such information, which has been developed in laboratory studies and pilot-plant studies during the past five years.

Photosynthesis.—Photosynthesis is the most basic process of biology. Through it green plants are able to make use of solar energy in appropriating carbon dioxide for incorporation into their own organic structure. Photosynthesis represents the ultimate origin of almost all organic matter and, thus, is

[3] "Sewage Lagoons in North Dakota," by W. Van Heuvelen and Jerome H. Svore, *Sewage and Industrial Wastes*, Vol. 26, 1954, p. 771.

[4] "Sewage Oxidation Ponds—Performance Operation and Design," by D. H. Caldwell, *Sewage Works Journal*, Vol. 18, 1946, p. 433.

[5] "Stream Sanitation," by Earle B. Phelps, John Wiley & Sons, Inc., New York, N. Y., 1944.

[6] "Sewage Treatment," by Karl Imhoff and G. M. Fair, John Wiley & Sons, Inc., New York, N.Y., 1940.

the only important mechanism by which solar energy is stored in a form available for living organisms. It is also the basic mechanism by which oxygen is released from water; oxygen in turn is the only substance that makes it possible for living organisms to gain sustained access to the energy stored in organic matter. More simply stated, the production of organic matter by photosynthesis is accompanied by the absorption of energy and the release of oxygen whereas the destruction of organic matter involves the utilization of an equivalent amount of oxygen and the release of energy. In general, the value of this equivalence of oxygen and any amount of a specific organic matter may be determined from the elementary composition of the organic matter when newly formed.

Photosynthesis in Sewage Treatment

It is generally recognized that organic matter is most rapidly oxidized biologically by bacteria, and there is much evidence that it is most rapidly syn-

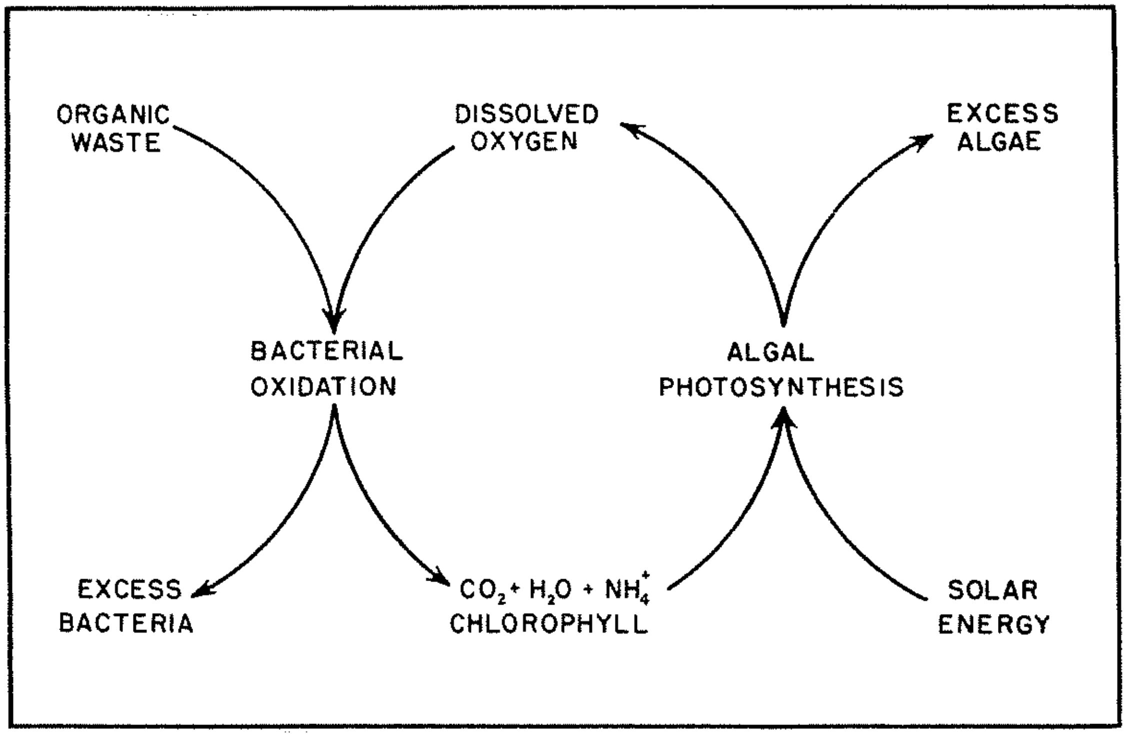

Fig. 2.—The Cycle of Oxygen and Algal Production in Sewage Treatment by Photosynthesis

thesized on a sustained basis by green algae. It is also well known that the principal products of aerobic bacterial oxidation of organic matter are CO_2, NH_3, and H_2O which, except for the additional requirement of light energy, are identical to the principal requirements for algal photosynthesis. Thus, in theory, the decomposition of organic matter by bacteria may occur at the same time that new organic matter is being synthesized by algae, provided that light is available as the energy source. Under such circumstances the efficiency of oxygen utilization is greatest because oxygen is used as soon as it is formed. This cycle of photosynthetic oxygen production is shown in Fig. 2. Organic matter entering the system as sewage is oxidized by sewage bacteria utilizing oxygen released by algae. The algae, utilizing solar energy, are simultaneously synthesizing organic matter from hydrogen liberated in their chlorophyll pigments and from the carbon dioxide and ammonia produced by bacteria. Although this entire reaction may occur in a closed system, some carbon dioxide is normally drawn into the cycle from the atmosphere and excess oxygen may be lost.

The cycle shown in Fig. 2 is the basic principle on which the Type 2 oxidation pond of Fig. 1 is operated. In order to develop practical equations for the design of such a unit, it is desirable to assume that it will be operated so that all the oxygen required by bacteria will result from the development of new photosynthate. It is desired also to evaluate some of the previously cited basic factors of photosynthesis and to express them in simple mathematical symbols. These factors are: (1) The relationship between oxygen and organic photosynthate; (2) the relationship between stored energy and organic photosynthate; and (3) the relationship between energy stored in organic photosynthate and the solar energy required to produce it.

The ratio of the weight of oxygen released, W_o, to the weight of organic matter synthesized, W_{om}, may be expressed as a factor, p:

$$p = \frac{W_o}{W_{om}} \qquad (1)$$

The available stored energy content, H, of the organic photosynthate is equal to its unit heat of combustion, h, times its weight, W_{om}, or

$$h = \frac{H}{W_{om}} \qquad (2)$$

The fraction of solar energy, E_s, fixed in the form of organic matter is equal to the total available heat energy, H, of the organic matter divided by a factor, F, which is the efficiency of energy conversion.

$$E_s = \frac{H}{F}, \quad \text{or} \quad F = \frac{H}{E_s} \qquad (3)$$

The ratios from Eqs. 1, 2, and 3 may be combined so as to show the basic relationships between algal cell concentration, depth, detention period, solar-energy input, and photosynthetic efficiency in photosynthetic oxygen production. These relationships may then be utilized with certain modifications to determine rational values for the physical dimensions of a pond of Type 2.

As shown by Eq. 3, the heat of combustion of algal cell material is proportional to the amount of the total light energy which has been fixed ($H = F\,E_s$). Because efficiency, F, is dimensionless, both H and E_s should be expressed in the same units. The energy, E_s, is related to insolation as follows:

$$E_s = S\,A\,D \qquad (4)$$

in which S is the insolation in langleys (gram-calories per square centimeter) per day; A is the surface area exposed to light, in square centimeters; and D is the time, in days.

Substituting in Eq. 3 the value of H from Eq. 2 and the value of E_s from Eq. 4,

$$S\,A\,D\,F = h\,W_{om}, \quad \text{or} \quad F = \frac{h\,W_{om}}{S\,A\,D} \qquad (5a)$$

in which W_{om} equals the weight of organic matter produced in area A and F is the efficiency of light utilization.

From the considerations shown in the development of Eq. 4, Eq. 3 may be written as

$$H = S\,A\,D\,F \qquad (5b)$$

The energy fixed in algal cells, H, may also be evaluated by multiplying the heat of combustion of the algae, h, by the concentration of algae, C_c, expressed in milligrams per liter rather than as W_{om}. Thus, $H = S\,A\,D\,F = h\,C_c$. Because the surface area, A, for one liter of liquid of depth, d, in centimeters is $1{,}000/d$ sq cm,

$$h\,C_c = \frac{S\,1{,}000\,D\,F}{d}, \quad \text{or} \quad D = \frac{h\,C_c\,d}{S\,1{,}000\,F} \qquad (6)$$

Since in deriving Eq. 6 the oxygen demand of a waste is assumed to be met through photosynthetic oxygen production, the biochemical oxygen demand, L_t, in any time, t, may be substituted for oxygen produced, W_o, and C_c may be substituted for W_{om}. That is,

$$p = \frac{W_o}{W_{om}} = \frac{L_t}{C_c} \quad \text{or} \quad C_c = \frac{L_t}{p} \qquad (7)$$

Combining Eqs. 5a and 7,

$$D = \frac{h\,L_t\,d}{1{,}000\,F\,S\,p} \qquad (8)$$

The efficiency, F, in Eqs. 6 and 8 is modified by many environmental factors.

The quantitative effects of each of the several environmental factors are not usually known. Experimental coefficients representing them can be determined, however, and then be applied to the factor, F. For example, temperature strongly affects both bacterial and algal growth. Hence, a temperature coefficient, T_c, is required in Eqs. 6 and 8.

$$d = \frac{h\,C_c\,d}{F\,T_c\,1{,}000\,S} = \frac{h\,L_t\,d}{F\,p\,T_c\,1{,}000\,S} \qquad (9)$$

Evaluation of the Design Equation

The actual application of Eq. 9 to the design of oxidation ponds depends on a knowledge of the interrelationships between the several factors in the equation in addition to the influence of environmental factors on the efficiency of algal and bacterial growth.

Depth.—The depth, d, necessary for a pond to produce by photosynthesis the oxygen required by a waste can be developed in terms of algal cell concentration, C_c. Experimental data have shown conclusively that a suspension of algal cells absorbs light, within close limits, in accordance with the Beer-Lambert law:

$$\frac{I}{I_i} = e^{-C_c \alpha d} \qquad (10)$$

in which I is the measured light intensity at depth d, I_i is the incident light intensity, and α is the specific absorption coefficient. Taking the natural log of both sides of Eq. 10,

$$\log_e I - \log_e I_i = -C_c \, \alpha \, d \qquad (11)$$

For a practical design it should be assumed that all the available light is absorbed; therefore, at the pond bottom the transmitted light, I, should be approximately zero. Equating I to 1.0 and solving Eq. 11 for d,

$$d = \frac{\log_e I_i}{C_c \, \alpha} \qquad (12)$$

If one neglects the possibility of unusual turbidity other than algal cells, Eq. 12 expresses the depth, d, to which light penetrates through a culture. Thus, Eq. 12 defines the effective depth for photosynthetic oxygen production inasmuch as there is no visible light and, hence, no algal growth below depth, d.

Because daylight intensities vary from a few hundred foot-candles to more than 10,000 ft-c and α and C_c vary between 1×10^{-3} and 2×10^{-3} and between 1×10^{2} and 3×10^{2}, respectively, it might seem that light intensity would have the greatest effect on the depth of light penetration. Actually light intensity may increase tenfold with but a 33% increase in the depth of penetration. On the other hand, reducing cell concentration by a factor of 2 will double the depth of penetration. The value of the coefficient α depends on the algal species and their pigmentation and is not normally subject to close control. In practice, however, it may remain approximately 1.5×10^{-3}. Hence, it may be concluded that algal cell concentration is the most important of three factors which determine the depth to which light will penetrate into a pond. The value of d determined from Eq. 12 is the depth which normally should be substituted in Eq. 6, Eq. 8, or Eq. 9.

Values of the Factor, h.—The heat content of algal cell material is a variable factor. It may be measured by calorimetric methods or computed from the chemical content of the algae. In general, it has been shown to be proportional to a factor termed the "*R*-value," which represents degree of reduction of the organic matter synthesized. If the percentage by weight of carbon, hydrogen, and oxygen in the organic matter is known, R may be determined. H. A. Spoehr and H. W. Milner[7] have shown that $R = \left(\frac{\% C \times 2.66 + \% H \times 7.94 - \% 0}{398.9}\right) 100$. It may also be shown that

[7] "The Chemical Composition of Chlorella; Effect of Environmental Conditions," by H. A. Spoehr and H. W. Milner. *Plant Physiology*, Vol. 24, 1949, p. 120.

there is a relationship between R and h which closely follows the empirical expression, $h = R/7.89 + 0.4$. Thus, a hypothetical material having an R-value of 60 should have a heat of combustion of about 8 kg-calories per gram. These relationships have been confirmed in the laboratory by calorimetric methods for algal cell material grown on sewage. Normally for sewage-grown algae, h is near 6 kg-calories per gram on an ash-free basis.

Values of the Factor, p.—The relationship between the weights of oxygen released and organic matter synthesized varies within relatively narrow limits. As in the case of h, one fundamental method for its evaluation is to measure carbon, hydrogen, oxygen, and nitrogen in the algal cell material. For example, an analysis of a certain culture of algal cells shows carbon to be 59.3%; hydrogen, 5.24%; oxygen, 26.3%; and nitrogen, 9.1%, on an ash-free, dry-weight basis. By dividing each of these percentages by the atomic weight of the corresponding element and by correcting the resulting numbers proportionately to make the value of the nitrogen coefficient equal to one, the following formula for algal cell material is developed: $C_{7.62}\,H_{8.08}\,O_{2.53}\,N_{1.0}$. Inasmuch as all evidence indicates that ammonia is the source of the nitrogen, carbon dioxide is the principal source of the carbon and water is the source of the oxygen, it may be assumed that the synthesis of this material is expressed by the equation,

$$1.0\,NH^+_4 + 7.62\,CO_2 + 2.53\,H_2O \rightarrow C_{7.62}\,H_{8.08}\,O_{2.53}\,N_{1.0} + 7.62\,O_2 + 1.0\,H^+.$$

Considering only cell material and oxygen on the right-hand side of the equation, $(12 \times 7.62) + (1 \times 8.08) + (16 \times 2.53) + (14 \times 1) = 153.56$ g cell material, and $(7.62 \times 32) = 243.84$ g oxygen, from which 1 g of cell materials is found to be equivalent to 1.587 g of oxygen. Because algal cell material may contain approximately 85% organic matter, the oxygen yield per gram of ash-included organic matter is 1.587×0.85 or approximately 1.35 g. Experimental work has shown that, under environmental conditions which are practical for photosynthetic oxygen production, the value of factor, p, is normally between 1.25 and 1.75. Thus, it may be concluded that synthesis of a unit weight of freshly produced algal cells has been accompanied by the production of a greater weight of oxygen in a form available for bacterial oxidation of organic matter.

Limitations on Efficiency.—It is to be expected that every factor affecting living cells will influence the efficiency with which green algae utilize solar energy. No firm value has been established for the maximum efficiency of photosynthesis although it may be more than 50% under certain conditions.[8] However, for purposes of application to sewage treatment, the question of maximum photosynthetic efficiency is largely academic because a practical barrier to high efficiency occurs long before the maximum reported values are reached.

This practical barrier is evolved from the fact that there is a maximum intensity of light which individual algal cells can utilize during a sustained period. All light energy supplied at a higher rate is therefore partly wasted. The critical light intensity above which no additional light is utilized has been termed the "saturation intensity," I_s. The importance of this factor in pond

[8] "Quantum Mechanism and Energy Cycle Process in Photosynthesis," by Dean Burk and Otto Warburg, *Naturwissenschaften*, Vol. 37, 1950, p. 560.

design is due to its effect in placing a practical upper limit on the efficiency, F, that can be used in Eqs. 6 and 8.

According to Vannevar Bush, as quoted by John S. Burlew,[9] the maximum fraction of available light that may be utilized by an individual alga is

$$f = \frac{I_s}{I_i}\left(\log_e \frac{I_i}{I_s} + 1\right) \qquad (13)$$

in which I_i is the incident light intensity, I_s is the saturation light intensity, and f is the fraction of the available light utilized.

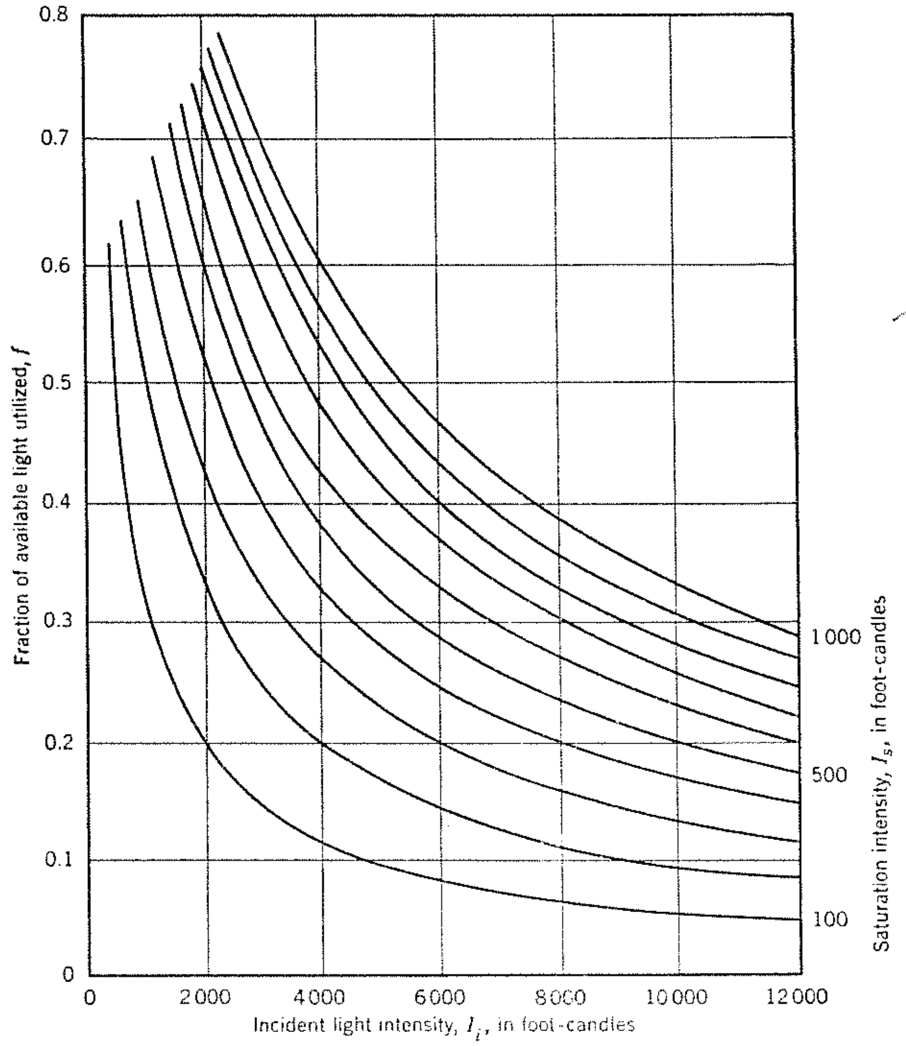

Fig. 3.—Influence of Saturation Intensity on Light Utilization by Algae

Fig. 3 shows graphically how f is influenced by changes in the incident and saturation light intensities. It is evident that, as the saturation intensity increases, the percentage of incident light which is utilized also increases. Thus, for example, for an I_i-value of 8,000 ft-c and an I_s-value of 400 ft-c, only 20% of the available light energy is utilized whereas, for an I_s-value of

[9] "Algal Culture from Laboratory to Pilot Plant," by John S. Burlew, *Publication 600*, Carnegie Institution of Washington, D.C., 1953.

700 ft-c, 30% of the energy is used. As I_i increases, f decreases regardless of the value of I_s. Investigations[9] have shown as one result of the foregoing that, if algal cells can be brought intermittently into contact with high-intensity light through turbulence created by vertical mixing, the percentage of available light that may be utilized is increased. This increase in the availability of light theoretically increases the depth which can be used in Eq. 6, Eq. 8, or Eq. 9 above that which might be determined from Eq. 12. Hence, the economically effective depth could be greater than the depth determined from Eq. 12. Further data are required, however, before any permissible increase in depth can be predicted under conditions of vertical mixing.

The value of I_s is not the same for all cultures of sewage-grown algae but rather it is a function of the physiological makeup of the particular cells in the culture. Their mechanisms for light absorption, hydrogen transfer, organic synthesis, and cell multiplication, when functioning at peak efficiency provide the highest saturation intensity. It has been previously demonstrated by the writers[10] that these functions are performed most effectively by young, rapidly

TABLE 1.—TEMPERATURE COEFFICIENTS FOR PILOT-PLANT CHLORELLA

Mean Temperature, in Degrees		Photosynthetic temperature coefficient, T_c
Centigrade	Fahrenheit	
0	32	...
5	41	0.26
10	50	0.49
15	59	0.87
20	68	1.00
25	77	0.91
30	86	0.82
35	95	0.69
40	104	...

growing cells. Thus, cultures in the logarithmic phase of cell growth attain a higher value of I_s and utilize a greater fraction of the available light than do older cultures. To support a population of young cells in the logarithmic phase of growth, a substrate rich in nitrogen and other vital elements is necessary. This condition is met only at short detention periods—that is, low values of D.

Only moderate values of efficiency are practical in sewage treatment because high values of F can occur only in substrates that are very rich in nutrients and hence are not stabilized. Values of F exceeding 10% are believed to indicate such a condition. Because the objective of sewage treatment is to produce a substrate depleted in organic matter, a relatively low average efficiency during the process is implied.

Temperature data are used to typify the manner in which photosynthetic efficiency is modified by environmental factors. In Table 1 are presented typical values for the temperature coefficient, T_c. This table is based on data for cultures of chlorella isolated in pilot-plant studies and grown in the laboratory

[10] "Algae Symbiosis in Oxidation Ponds. II. Growth Characteristics of *C. pyrinoidosa* Cultured in Sewage," by W. J. Oswald, H. B. Gotaas, H. F. Ludwig, and V. Lynch, *Sewage and Industrial Wastes*, Vol. 25, 1953, p. 26.

at a light intensity of 1,200 ft-c, illuminated an average of 14.4 hr daily, and at a detention period of 4 days. As previously indicated different values of T_c might be obtained under different experimental conditions and with different species of algae. This fact is illustrated by the observation that the dominant species of algae in an oxidation pond tends to change with the seasons.[11] Sustained low temperatures require consideration. Data obtained in the laboratory indicate that low-temperature adaptation is a characteristic of the chlorella encountered in pilot-plant studies.[11] This strain. or comparable strains of algae, may be expected to occur in low-temperature ponds and will sustain photosynthetic oxygen production at temperatures nearly as low as freezing. However, as shown in Table 1, temperature coefficients which modify efficiencies are greatly reduced at the lower temperatures. The rate of bacterial oxidation of sewage is also reduced at low temperatures, and it may become reduced to a point where little oxidation is accomplished regardless of the oxygen supply. In regard to high temperatures, a strain of chlorella that has a high temperature tolerance has been reported by Jack Myers.[12] This and other strains will undoubtedly develop under favorable conditions particularly if afforded an adaptation period.

Values of the Factor, S.—The daily amount of solar energy, S, that reaches the earth's surface is a function of astronomical, geographical, and meteorological phenomena. As might be expected it is subject to wide daily and seasonal variation, but on a monthly basis it may be closely predicted at any particular location if certain geographical and meteorological data are available. Table 2 represents predicted maximum and minimum plausible values of S for the indicated segment of the earth, as computed by the writers from relationships published by H. H. Kimball[13] together with other data collected and published by the Weather Bureau (United States Department of Commerce).[14,15] Use of Table 2 to determine the value of S is illustrated by the following example:

The numbers in the columns under each month represent the visible and total insolation (solar radiation), both direct and diffuse, incident on a horizontal surface at sea level, expressed in langleys (gram-calories per square centimeter) per day. Values in the right-hand column for any month are total insolation (ultraviolet, visible, and infrared) whereas those in the left-hand column are the portion of this total radiation which lies in the visible range—that is, the amount of radiation of wave lengths from 4,000 A° to 7,000 A° that will penetrate a smooth water surface. The maximum (max) values represent in each case the average daily amount of radiant energy which may be received during clear weather. These maximum values have been computed taking into consideration all the important factors influencing insolation. Hence,

11 "Photosynthetic Reclamation of Organic Wastes," by H. B. Gotaas, W. J. Oswald, and H. F. Ludwig, *Scientific Monthly*, Vol. 79, 1954, p. 368.

12 "Growth Characteristics of Algae in Relation to the Problems of Mass Culture," by Jack Myers, *Publication 600*, Carnegie Institution of Washington, 1953.

13 "Intensity of Solar Radiation at the Surface of the Earth and its Variations with Latitude, Altitude, Season, and Time of Day," by H. H. Kimball, *Monthly Weather Review*, Vol. 63, 1935, p. 1.

14 "Solar Radiation Data by Stations," *Monthly Weather Review*, U. S. Dept. of Agriculture, Nos. 71–77, U. S. Govt. Printing Office, Washington, D. C.

15 "Solar Radiation Data Annual Summary," *Climatological Data: National Summary*, U. S. Dept. of Commerce, Nos. 1-3, U. S. Govt. Printing Office, Washington, D. C., 1943–1953.

TABLE 2.—SOLAR RADIATION[a]; PROBABLE AVERAGE VALUES
SURFACE AT SEA LEVEL,

North Latitude		Month											
Degree	Range	January		February		March		April		May		June	
		vis[c]	tot[d]	vis	tot	vis	tot	vis	tot	vis	tot	vis	tot
0	max[e]	255	685	266	700	271	708	266	690	249	645	236	626
	min[f]	210	580	219	583	206	536	188	462	182	489	103	274
2	max	250	670	263	693	271	706	267	697	253	655	241	642
	min	206	560	213	560	204	534	188	464	184	484	108	288
4	max	244	650	259	688	270	704	268	701	258	665	247	656
	min	200	540	206	543	202	532	187	466	187	492	113	300
6	max	238	630	254	675	268	702	270	705	262	675	252	668
	min	193	520	199	530	200	530	186	467	189	500	118	310
8	max	230	610	249	665	267	700	270	709	266	685	258	678
	min	187	495	192	510	196	523	185	467	191	506	124	320
10	max	223	595	244	655	264	694	271	711	270	694	262	688
	min	179	475	184	490	193	513	183	464	192	512	129	330
12	max	216	572	239	645	262	690	271	710	273	702	267	700
	min	172	455	176	470	189	500	181	462	193	518	133	343
14	max	208	555	233	630	258	680	271	709	276	710	272	710
	min	163	430	167	450	184	487	179	460	194	524	137	354
16	max	200	530	226	610	255	670	272	707	279	718	276	720
	min	154	400	159	430	180	473	177	456	194	528	141	363
18	max	192	515	220	590	250	664	272	705	282	723	280	728
	min	144	380	150	410	174	459	174	452	194	530	145	375
20	max	183	500	213	575	246	652	271	703	284	730	284	738
	min	134	360	140	390	168	440	170	447	194	532	148	383
22	max	174	480	206	560	241	644	270	701	286	734	286	747
	min	123	335	132	370	162	426	167	440	193	530	152	392
24	max	166	460	200	545	236	625	268	697	288	738	290	753
	min	111	310	123	340	156	410	164	433	191	525	155	403
26	max	156	440	192	530	230	615	266	690	288	741	292	760
	min	99	280	114	310	149	390	160	425	189	518	158	409
28	max	146	420	184	510	224	603	264	683	289	743	294	764
	min	87	250	106	290	142	373	156	415	187	506	161	418
30	max	136	400	176	490	218	587	261	675	290	744	296	768
	min	76	220	96	260	134	362	151	405	184	490	163	425
32	max	126	380	169	470	212	570	258	663	290	744	296	772
	min	63	180	87	240	126	340	146	395	181	475	166	431
34	max	114	360	160	450	204	553	254	657	290	743	297	775
	min	53	155	78	215	118	320	141	385	176	462	168	439
36	max	103	335	150	430	196	538	250	650	288	741	298	776
	min	44	133	70	200	111	300	136	375	172	444	170	443
38	max	90	310	140	415	189	520	246	640	287	738	298	778
	min	36	120	62	180	103	280	131	365	166	428	171	448
40	max	80	280	130	390	181	500	241	630	286	732	298	778
	min	30	105	53	160	95	270	125	355	162	415	173	450
42	max	68	255	119	370	172	485	236	618	283	728	298	777
	min	24	90	45	140	88	250	120	344	157	405	174	451
44	max	55	228	106	340	165	470	230	607	280	722	298	777
	min	20	80	37	130	80	230	114	325	153	395	175	453
46	max	45	200	94	315	156	450	224	598	278	716	298	776
	min	16	74	30	110	72	210	108	315	150	385	175	455
48	max	35	180	82	290	149	430	218	582	274	710	297	776
	min	12	64	25	99	64	190	102	307	146	378	176	458
50	max	28	164	70	265	141	410	210	568	271	703	297	776
	min	10	54	19	80	58	173	97	300	144	371	176	458
52	max	22	140	60	240	134	390	202	555	267	695	296	776
	min	8	45	14	62	51	158	92	295	141	366	176	460
54	max	16	120	50	215	126	370	194	542	263	687	296	776
	min	6	40	11	45	46	145	88	289	139	360	176	460
56	max	12	102	43	200	120	350	188	528	258	680	295	775
	min	4	35	8	35	41	132	85	283	136	352	175	460
58	max	9	80	37	170	113	330	182	516	254	670	294	774
	min	3	28	6	28	37	118	82	277	134	346	175	460
60	max	7	64	32	150	107	310	176	500	249	660	294	773
	min	2	20	4	20	33	105	79	270	132	340	174	460

[a] Calculated from data published by the Weather Bureau. Approximate corrections for elevation up to 10,000 ft: (1) Total radiation = (total at sea level) (1 + 0.0185 × El.), and (2) Visible radiation = ("visible" at sea level) (1 + 0.00925 × El.). Correction for cloudiness (approximate): Min + [(max − min) cl.] in which cl. is the fraction of time the weather is clear. [b] Gram calories per square centimeter. [c] "Visible" = radiation

OF INSOLATION—DIRECT AND DIFFUSE—ON A HORIZONTAL IN LANGLEYS[b] PER DAY

Month												North Latitude	
July		August		September		October		November		December		Range	Degree
vis	tot	vis	tot	vis	tot	vis	tot	vis	tot	vis	tot		
238	630	252	666	269	690	265	694	256	683	253	667	max	0
137	368	167	432	207	533	203	530	202	543	195	527	min	
244	646	255	673	269	693	262	688	251	666	249	646	max	2
141	375	169	442	206	531	200	523	198	526	189	505	min	
250	657	258	678	269	695	260	680	246	650	244	628	max	4
146	385	171	448	204	529	196	513	194	510	183	480	min	
255	669	261	683	269	697	256	670	240	634	238	610	max	6
150	395	172	452	202	524	191	500	188	494	176	460	min	
260	680	263	688	267	695	252	660	234	616	231	590	max	8
154	405	174	456	200	518	186	486	182	478	169	440	min	
265	690	266	693	266	693	248	650	228	600	225	570	max	10
158	414	176	460	196	510	181	474	176	462	162	420	min	
269	700	267	697	264	691	244	640	221	585	217	550	max	12
161	421	176	464	193	502	176	462	169	446	154	400	min	
273	708	269	700	262	688	240	627	214	567	209	536	max	14
164	429	177	467	189	496	170	449	162	430	146	380	min	
277	715	270	703	259	684	234	615	206	554	200	520	max	16
167	435	177	469	185	489	164	434	154	410	138	360	min	
280	723	272	705	256	680	229	605	198	538	192	500	max	18
170	442	177	471	180	479	157	418	146	390	129	340	min	
282	729	272	706	252	674	224	596	190	520	182	480	max	20
172	450	177	472	176	467	150	400	138	370	120	320	min	
285	736	273	707	248	668	218	582	183	500	172	460	max	22
173	454	176	472	170	455	143	380	128	350	110	300	min	
287	742	273	708	244	659	212	568	175	480	161	440	max	24
176	459	174	471	165	443	136	360	119	326	101	280	min	
288	749	273	706	240	652	205	552	166	460	149	420	max	26
177	463	172	469	160	429	128	332	109	300	90	260	min	
288	755	272	704	236	635	199	537	157	440	138	400	max	28
178	467	169	466	154	415	120	310	99	278	80	236	min	
289	759	271	702	231	625	192	524	148	420	126	380	max	30
178	469	166	462	147	399	113	290	90	256	70	210	min	
289	761	269	700	226	615	185	510	138	400	114	360	max	32
178	472	163	458	140	385	104	270	80	224	60	184	min	
289	763	267	696	221	602	178	490	128	380	101	338	max	34
178	472	159	448	134	368	96	250	70	202	47	158	min	
289	765	264	690	215	590	170	470	118	360	88	314	max	36
177	470	155	438	127	350	88	230	60	180	39	134	min	
288	766	262	684	210	576	162	450	106	336	77	290	max	38
175	464	152	429	120	330	80	216	50	158	30	111	min	
288	765	258	680	203	562	152	430	95	313	66	270	max	40
172	455	147	416	112	310	72	202	42	134	24	94	min	
287	761	254	670	196	547	144	410	84	289	56	244	max	42
167	442	143	403	105	290	65	187	34	112	19	78	min	
285	755	250	660	189	530	132	390	72	263	47	218	max	44
164	430	139	389	98	270	58	173	28	98	15	62	min	
284	749	245	650	181	512	122	370	61	238	39	194	max	46
161	420	134	374	90	250	52	158	23	86	11	48	min	
282	740	241	640	174	496	111	350	50	210	32	170	max	48
158	410	129	358	81	230	45	144	18	70	9	37	min	
280	733	236	625	166	480	100	329	40	183	26	144	max	50
155	403	125	342	73	210	40	130	15	60	7	30	min	
278	725	232	615	158	460	87	307	32	160	21	121	max	52
153	398	120	326	65	190	34	120	12	53	4	27	min	
276	720	224	602	150	440	76	285	25	140	16	99	max	54
150	394	116	312	58	170	29	106	9	43	3	23	min	
273	714	218	587	141	420	64	261	20	120	12	78	max	56
148	390	110	297	51	150	24	95	7	36	2	18	min	
270	710	212	575	134	402							max	58
146	385	106	285	44	132							min	
268	708	205	556	126	386							max	60
144	380	100	270	38	116							min	

of wave lengths of 4,000 A° to 7,000 A° penetrating a smooth water surface. [d] "Total" = radiation of all wave lengths in the solar spectrum. [e] Value which will not normally be exceeded. [f] Value based on, or extrapolate from, lowest values observed for indicated month and latitude during ten years of record.

there is little chance that any particular value will be exceeded during the month for which it is listed. Minimum (min) values represent average daily amounts that may be received during weather with heavy incidence of clouds. These minimum values reflect graphic interpolations or extrapolations of minimum

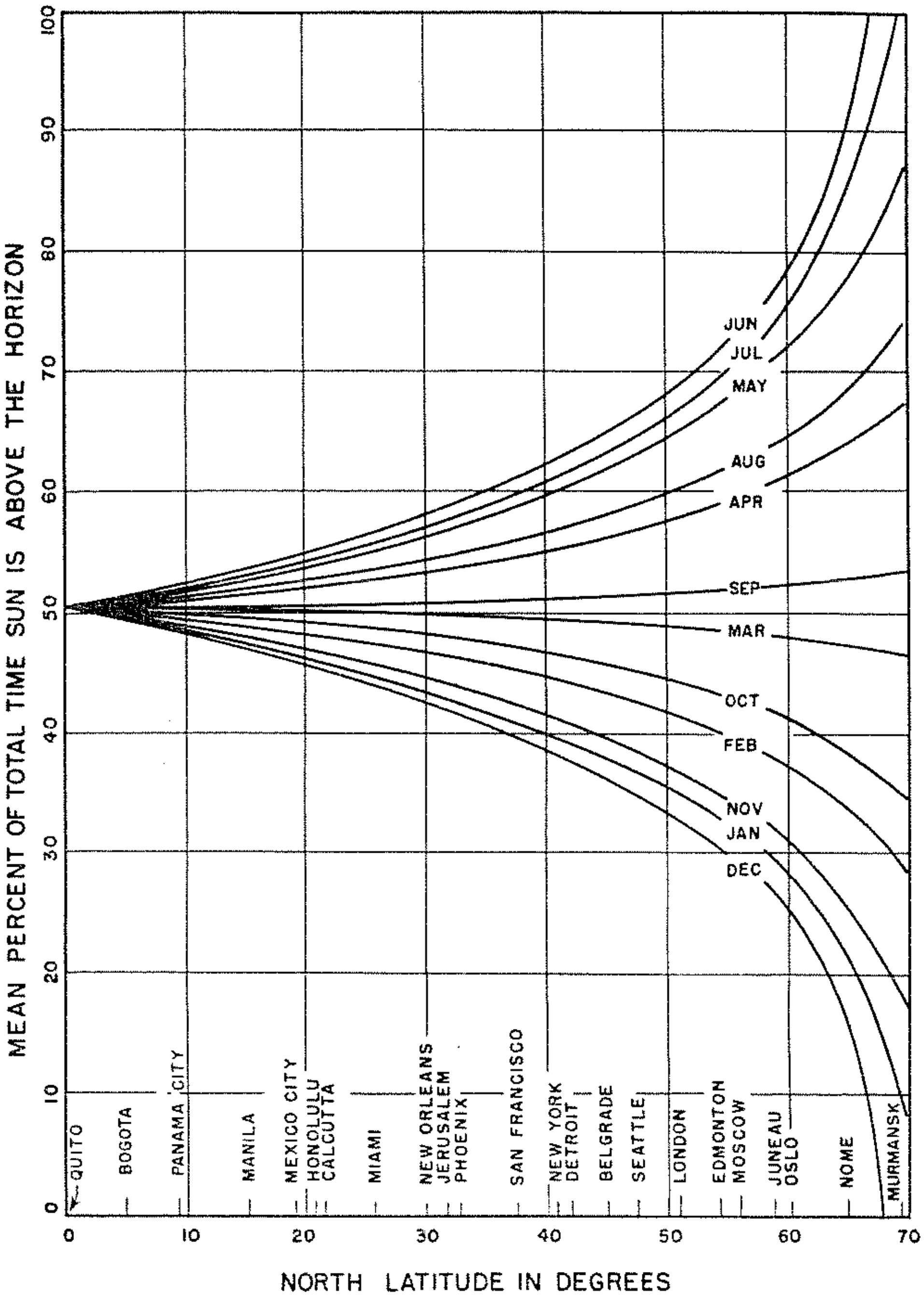

FIG. 4

observations reported in Weather Bureau records during the ten-year period, 1943 to 1952, inclusive. Thus, although these minimum values do not reflect the most cloudy days of record, there is little chance that any of the stations will experience monthly averages appreciably lower.

When corrections are made for elevation and cloudiness in the manner noted at the bottom of Table 2, values of visible radiation obtained from the table may be used as a quantitative measure of the energy available for photosynthesis—that is, as values of S to be used in Eq. 6, Eq. 8, or Eq. 9.

Table 2 may also be used in connection with Fig. 4 in order to estimate a value of I_i to be substituted in Eq. 12 to determine an approximate value of d for use in Eq. 6, Eq. 8, and Eq. 9. Studies by the writers have shown that the mean light intensity at a point for the entire twenty-four hour period of a day is about ten times the total insolation expressed in langleys per day, multiplied by the fraction of the time the sun is visible. A value so estimated is altered by many variable factors and is not subject to precise evaluation. However, this method is relatively accurate for determining the average light intensity during a period of time and may be used for the estimation of I_i by the following steps:

1. The total solar radiation is determined from Table 2.
2. The necessary corrections are made for elevation and cloudiness.
3. The resulting value is multiplied by 10.
4. One evaluates I_i for use in Eq. 12 by multiplying the result of step 3 by the fraction of time the sun is visible for the appropriate latitude and month as determined from Fig. 4.

For example, following the foregoing steps a station at latitude 37°, El. 2000, with clear weather 50% of the time may have a mean light intensity in December of approximately 870 ft-c on a horizontal surface.

Influence of Chemical Factors

Nitrogen.—The writers[16] have collected considerable evidence indicating that the species of algae which are effective in photosynthetic oxygen production utilize ammonia as the principal source of nitrogen with which to build their proteinaceous cell material. At moderately long detention periods of 3 days or 4 days when temperature and light are optimum, almost all the available ammonia nitrogen appears in the form of algal cell material. In this way nitrogen is conserved and at the same time the ultimate oxygen demand of a waste material is greatly diminished because little ammonia remains to be oxidized to nitrate.

Under some conditions, supernatant analyses show the presence of reduced nitrogenous compounds. Although there can occur a small carry-over of sewage unoxidized during the short detention periods normally effective in the process, the quantity of these compounds increases with increasing detention periods; this fact indicates that a small amount of inseparable organic matter is produced in the process. A portion of the nitrogenous material is fixed in living bacterial cells, which are dispersed as colloids and are discharged in the supernatant liquid. Whatever the nature of this supernatant nitrogen, under proper operating conditions it normally amounts to less than one-third the total nitrogen in the waste while the remainder appears in the algal cells.

[16] "Algae Symbiosis in Oxidation Ponds. III. Photosynthetic Oxygenation," by W. J. Oswald, H. B Gotaas, H. Ludwig, and V. Lynch, *Sewage and Industrial Wastes*, Vol. 25, 1953, p. 692.

The nitrogen content of a waste material places a practical upper limit on the concentration of cell material which can be developed from it. A useful rule-of-thumb relationship between sewage nitrogen and growing algae is that $C_c = 10 \times N$, in which C_c (the maximum algal cell concentration) and N (nitrogen) are expressed in the same units. The constant 10 stems from the assumption that 80% of the nitrogen in the waste is recovered and that algal cells are 8% nitrogen. For example, it has been observed that a waste material containing 30 ppm of total nitrogen will support $0.8 \times 30/0.08 = 300$ ppm of algal cells before nitrogen becomes a limiting factor to cell growth.

Phosphorus.—Phosphorus rarely becomes a limiting factor to algal growth in sewage. The best information now available indicates that phosphorus does not normally exceed 1.5% of the dry weight of algae. In this case a typical

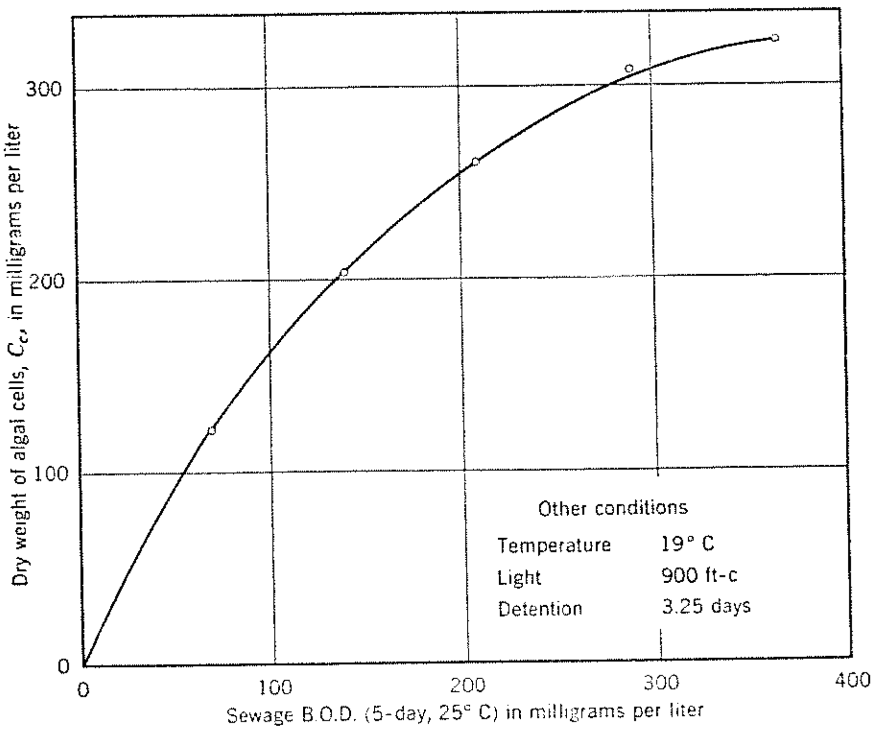

FIG. 5.—EFFECT OF B.O.D. ON THE CONCENTRATION OF ALGAL CELLS IN CONTINUOUS CULTURES

sewage containing 6 ppm or more of phosphorus would sustain an algal concentration of 400 ppm or more if all the phosphorus were available. Increased use of detergents in the home and in industries makes it unlikely that either phosphorus or nitrogen (both components of detergents) will be limiting factors in the nutritional makeup of domestic sewage.

Magnesium and Potassium.—Both magnesium and potassium are essential to algal growth. Magnesium is essential because it is an integral part of the chlorophyll molecule, and potassium because salts of this metal are prime constituents of algal cell sap. Normally domestic sewage contains more than 5 ppm of both these elements. Since algal cells may contain 0.5% potassium and 1% magnesium, it can be concluded that if these elements are fully available domestic sewage contains them in sufficient amounts to support algal concentrations in excess of 500 ppm.

Carbon.—Carbon is usually the limiting element when algae are cultured in sewage. However, the use of artificially introduced carbon is neither essential nor desirable when algae are cultured in sewage for purposes of photosynthetic production of oxygen. Although the amount of carbon contained in sewage may be inadequate to produce growths large enough to meet the oxygen demand of the waste, the culture may also obtain carbon dioxide from the air. Active photosynthesis causes the pH to increase to 10 or more, accelerating the absorption of atmospheric CO_2 by the culture. Under such conditions this CO_2 appears in the solution as a bicarbonate ion and becomes available to the algae at once. From this fact it is seen that algae may compensate for a shortage of CO_2 by increasing the CO_2 absorbing properties of the solution in which they grow.

Biochemical Oxygen Demand.—The B.O.D. test is unique in its significance as a measure of the response of microbial growth to the nutritional character of wastes. Fig. 5 shows the effect of the B.O.D. of a sewage on the algal growth it will support. It is noteworthy that in continuous cultures such as those reported in Fig. 5 the dry weight of algal cell material appears to be a logarithmic function of B.O.D. up to approximately 400 ppm. Evidence indicates that for B.O.D.-values greater than 300 ppm light rather than nutrition is normally limiting to outdoor algal growth. The effect of increasing light intensity above that shown for the tests in Fig. 5 would be to increase culture density slightly. However, the shape of the curve would remain similar.

Actual laboratory tests are needed to determine whether a given domestic sewage will support enough algal growth to produce its oxygen requirements by photosynthesis.

Design Considerations

Detention Period.—Inasmuch as the detention period, D, as shown in Eq. 9 is a function of light and temperature, theoretically it should be capable of much greater variation than is possible in practical pond design. For example, to apply Eq. 9 to a sewage having a B.O.D. of 150 ppm under December conditions at latitude 37°, it may be assumed that $p = 1.5$, $h = 6.0$, $d = 30$ cm, $F = 0.1$, and $T_c = 0.87$. From Table 2, S (min) may be taken as 34 langleys per day. Using these values it is computed that a detention period of nearly 6 days might be required for complete sewage treatment. In the summertime the efficiency of a pond designed for such a detention period would become very low. Without proper variations in operating procedures the result could be overproduction of algae, a part of which might die and be decomposed, thus producing a pond effluent having a high supernatant B.O.D. On the other hand, if a pond were designed for the same location on the basis of June light and temperature conditions using S (average) $= 234$, $T_c = 1.0$, and other factors remaining the same, from Eq. 9 a detention period of only 0.77 day is determined. Pilot-plant units have been successfully operated at detention periods as low as 0.75 day for sustained periods with otherwise optimum environmental conditions, and chlorella as well as other algae easily maintain a rate of growth sufficient to prevent being diluted out of the pond under these conditions. However, it has been found from pilot-plant experience that cultures cannot withstand either low temperatures or a long succession of cloudy days at this low detention period without some nuisances occurring. Hence, if a pond were to be designed for the June conditions previously stated, it would be better to increase the detention period and the pond depth. For the stated June conditions of light and temperature the depth, d, determined from Eq. 12 is increased to 48 cm, in which case the detention period determined from Eq. 9 would become 1.25 days, a value more in keeping with the growth capabilities of organisms under varying outdoor conditions. In order to provide a detention period suitable for effective photosynthetic oxygen production in both winter and summer and with "buffer capacity" against changes in light and temperature and against shock loading, certain compromises are necessary. In some cases it might be feasible to design with the expectation that only about 50% of the B.O.D. would be removed by the process in winter when, because of low temperatures and higher stream flow, complete treatment should not be necessary. It would be unnecessary to produce oxygen photosynthetically when the temperature was too low for a high rate of bacterial oxidation.

In general, it may be concluded that for most conditions detention periods should not be less than 1 day for summer conditions nor more than 6 days for winter conditions. A pond having a detention period of about 3 days and a depth of 12 in. should, for example, satisfactorily produce adequate oxygen by photosynthesis more than 80% of the time in latitudes up to 40° north, providing that continuous freezing conditions do not prevail. Under summer conditions it may be computed that Type 2 ponds should operate successfully as far north as the arctic circle or beyond.

Depth.—As previously shown by Eq. 12, the depth of a pond depends on light intensity for effective photosynthetic oxygen production as well as on light absorption and algal cell concentration. From Eq. 9 it may be observed that computed depth varies greatly with both the cell concentration, C_c, and the sewage strength, L_t. Strong wastes requiring dense algal growths must therefore be treated in relatively shallow ponds whereas weak domestic sewage may be processed at larger depths. The appropriate depth required for treating a particular sewage may be computed as illustrated in the following example. Assuming that the sewage has a B.O.D. of 125 ppm, p is 1.25, I_i has a mean value of 1,500 ft-c, and α is 1.2×10^{-3}, then from Eq. 12,

$$d = \frac{\log_e I_i}{\alpha C_c} = \frac{\log_e 1{,}500}{1.2 \times 10^{-3} C_c} \approx \frac{6{,}000}{C_c}.$$

From Eq. 7

$$C_c = \frac{L_t}{P} = \frac{125}{1.25} = 100.$$

Hence,

$$d = 6{,}000/100 = 60 \text{ cm, or approximately 2 ft.}$$

Organic matter at depths below this value would presumably be in darkness and not subject to photosynthetic oxygenation. If a waste material with a B.O.D. of 1,250 ppm had been utilized in the computations, a depth of light penetration of less than 3 in. would have been determined. Economic utilization of land, pond-construction costs, mixing methods, and similar factors place a practical lower limit on the depth of the pond and a practical upper limit on the concentration of wastes. For instance, wastes of B.O.D. greater than 300 ppm result in computed depths so shallow that pond areas become very large. In such cases vertical mixing or primary dilution should be considered as alternatives to shallow depths.

Deposition of Sludge.—Rapid oxidation of organic matter in a pond accelerates the deposition of sludge, which may become so dense near the pond inlet as to include more than 50% of the influent organic matter. Such sludging has been observed in oxidation ponds of all types, especially in those having only a few inlets. Small ponds and long narrow ones are more subject to this difficulty than are large ponds or broad ponds, indicating that wind mixing is beneficial in the open structures. These anaerobic sludge deposits tend to exclude light, retain nutrients needed by the algae in the liquid, and, hence, decrease permissible pond depth. Suggestions for combating sludging by proper design considerations include reduction of depth, increasing dilution factor, distributing the load by multiple inlets, orientation of the pond to obtain wind mixing, and producing turbulence by vertical mixing.

If a Type 2 pond is to be maintained aerobic by photosynthetic oxygen production despite sludge deposition, it must be kept shallow so that light penetrates a relatively large portion of the volume, or some form of vertical mixing must be used. Present evidence indicates that vertical mixing is particularly desirable if algal cell recovery is to be practiced. In this case maximum algal growth is encouraged because the products of bacterial oxidation are made uniformly available to the algae in the light. It is probable that some artificial vertical mixing must be considered an essential feature for Type 2 oxidation ponds. Mixing, however, must not be prolonged because the resultant increase in turbidity decreases light penetration, hindering photosynthesis.

Recirculation.—Pilot-plant studies have indicated that recirculation is important to photosynthetic oxygen production because it permits seeding of influent sewage with algal cells and brings abundant oxygen into it. In other words, recirculation produces good overlapping of bacterial oxidation and of photosynthetic reduction, thereby preventing loss of CO_2 and ammonia from the bacterial phase and providing an efficient outlet for the oxygen liberated by algal growth.[10] This overlapping produces more abundant growths of bacteria and would produce more abundant growths of algae were it not for the problem of sludge deposition. Algae tend to remain dispersed in the solution whereas bacteria tend to form a floc which, together with coagulated sewage colloids containing a large part of the carbon and nitrogen, settles quite rapidly to the bottom of the pond. Some recirculation accelerates sludge deposition with the accompanying possibility of anaerobic conditions in the sludge layer as well as the withholding of nutrients from the algae in the liquid. Because the principal benefits of recirculation are seeding and aeration of the influent, it is possible that these benefits may be duplicated by increasing the uniformity of load distribution together with a low rate of recirculation to accomplish seeding.

Retention of Sludge.—If continuous vertical mixing is used some aerobic sludge may be carried into the pond effluent. This material may be readily removed from the algal suspension by sedimentation and returned to the pond.

If intermittent vertical mixing is used, carry-over of sludge may be prevented by interrupting the discharge of effluent during and shortly after the mixing period. In either case, retention of sludge is advantageous because it allows more complete oxidation of the organic matter, resulting in increased algal growth and improved removal of suspended solids other than algae.

The Need for Paving.—Several factors suggest the possibility that there may be important advantages gained by lining oxidation ponds of Type 2. Any form of vertical mixing considered essential for raising precipitated sludge and increasing light utilization might cause undue turbidity in unpaved ponds. The result would be reduction if not termination of photosynthesis. Furthermore, unpaved ponds designed to make full use of winter sunlight might have excess light at the bottom in the summer, a factor which would probably encourage growth of water weeds such as tule.

Asphaltic or rubber membranes sprayed over shaped and compacted earth appear to be an economic type of pond lining. Sealed asphaltic concrete or thin reinforced concrete would have the advantage of durability and low maintenance. The possibility of application of commercially manufactured preformed channels of plastic or aluminum should not be overlooked. The design and fabrication of economical pond linings does not appear to be a difficult technical problem because the indicated pond size of nearly one-half acre per thousand population is not prohibitively large. The decision on linings depends primarily on the value of photosynthate in the sewage treatment process.

Disposal of Algae.—In the process of producing controlled quantities of oxygen for bacterial stabilization of waste, the concentration of algae produced in moderately strong domestic sewage (200 ppm B.O.D.) may attain levels in excess of 300 ppm, dry weight. Two questions immediately arise: (1) If algae are discharged with the pond effluent, what is the effect on a receiving body of water; and (2) can these algae be economically separated from the effluent?

In answer to the first question, it should be noted that there is a limit to the concentration of algae that can survive in any body of water for a sustained period of time. Algal cells are living organic matter which may grow, vegetate, or die. If the cells grow they will produce oxygen. If they vegetate they will have a small but finite continuous oxygen demand. (For sewage-grown algae by Warburg measurement, this usually is about one-tenth the ash-free dry weight of cells per day at 25° C.) If they die they will be decomposed like any other organic matter. Which of these three possible avenues the cells will first take depends on the environment in the receiving water. As discussed by the writers in an earlier paper,[17] if the receiving water contains nutrients (indicating pollution) and light, the cells will grow and divide, thus producing oxygen. If there is light but few nutrients, the cells will vegetate for long periods of time producing little objectionable pollution in a stream. Cultures of algae having concentrations of 200 ppm or 300 ppm have been held for three months without putrefaction as long as light and access to atmospheric CO_2 are afforded. Ultimately, however, the cells will settle to the bottom. In the dark, algae remain alive for a length of time, which is principally a function of temperature. Algal

[17] "Algae Symbiosis in Oxidation Ponds. I. Growth Characteristics of *E. gracilis* Cultured in Sewage," by H. F. Ludwig, W. J. Oswald, H. B. Gotaas, and V. Lynch, *Sewage and Industrial Wastes*, Vol. 23, 1951, p. 1337.

cells will keep in the dark for 2 weeks at temperatures near freezing but will die and be decomposed in a few days in the dark at temperatures above 25° C. It may be concluded that living algal cells will do little pollutional damage to receiving waters unless their concentration is so large that their endogenous respiration depletes the oxygen reserve of the water. However, should the algal cells for some reason be killed in the receiving waters, they will exert an oxygen demand approximately equivalent to their dry weight.

Economical separation of algal cells is a highly important aspect of the general use of photosynthesis in sewage treatment. At least two systematic investigations have been conducted recently on algal separation, and three processes have been demonstrated to be technically effective. Two of these processes, centrifugal separation and alum coagulation, have been partly investigated by the writers and other methods are scheduled for investigation. E. W. Steele, M. ASCE, and E. F. Gloyna, A.M. ASCE,[18] performed a series of investigations on screening and filtering devices for separating algae. These showed rather conclusively that separation of algae is a difficult and costly procedure which may require extensive research and development before the most economical procedures are established.

Because of the relatively low concentration at which algae grow, the cost of separation is almost completely proportional to the volume of liquid processed and relatively independent of the concentration of algae in the liquid. Therefore, some level of algal concentration may be attained which will pay for the cost of harvesting, and some higher concentration might support the entire photosynthetic process.

Pond Performance

Algal Yields.—Pilot-plant observations summarized in Fig. 6 show that the rate of algal yield may vary from 1 ton per acre per month in the winter to 5 tons per acre per month in the summer. The total annual rate of yield was 30 tons per acre. In order to visualize such yields, it is useful to compare yields of algae to field crop yields. During 1953 the average field crop yield in California was less than 1.5 tons dry weight per acre per year. Thus, the rate of yield attained in the pilot plant was twenty times the agricultural average. The actual annual yield of algae may be expected to vary strongly with light and temperature and, hence, with geographical location.

B.O.D. Removal.—The operation of an oxidation pond to produce maximum algal yields can at the same time accomplish a high degree of sewage treatment in terms of B.O.D. removal. Data from pilot-plant experiments shown in Table 3 demonstrate that effluents of the quality desired in sewage treatment may be produced. It is believed that samples 2, 3, and 4 would have exerted much less B.O.D. in a stream than is indicated from the data because the residual algae would have continued to produce some oxygen following discharge.

Coliform Removals.—In laboratory and pilot-plant tests no reduction in coliform organisms other than normal die-away has been noted, except in cer-

[18] "Oxidation Ponds-Radioactivity Uptake and Algae Concentration," by E. W. Steele and E. F. Gloyna, *Technical Report No. 1*, AECU-2837, U. S. Atomic Energy Commission, Technical Information Service, Oak Ridge, Tenn., 1954.

tain light-saturated cultures. In these cultures it is probable that the germicidal effect of natural sunlight was responsible. In other words, no specific anticoliform activity can be credited to the algae produced in the cultures tested. These findings were supported by inoculating with human intestinal

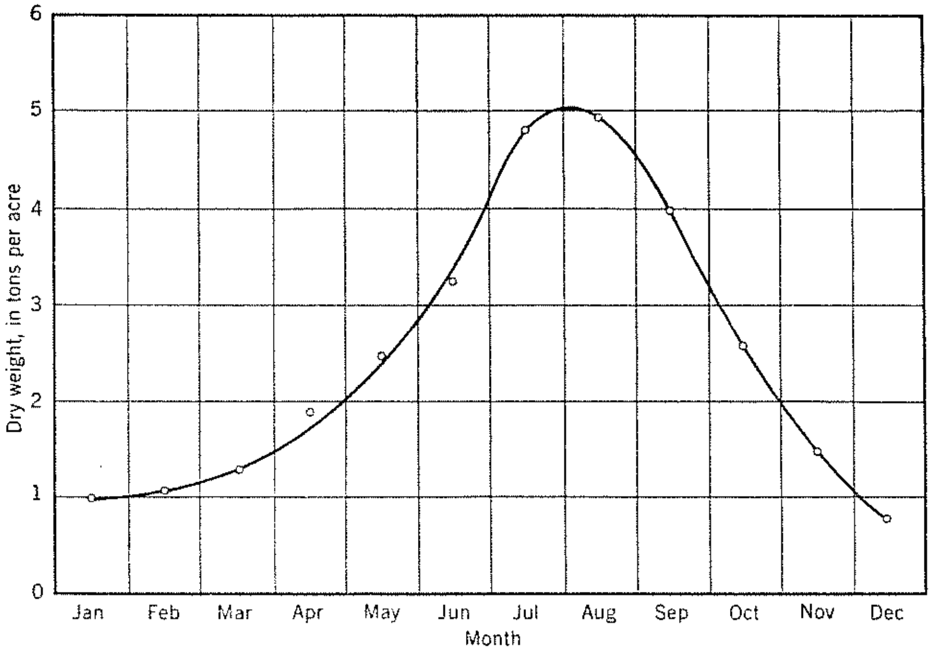

FIG. 6.—ESTIMATED MONTHLY YIELDS OF ALGAE FROM DOMESTIC SEWAGE AT RICHMOND, CALIF.

coliform a solid medium made up with 25% porcelain-filtered pond supernatant. The fact that the coliform organisms were found to grow abundantly in this medium indicates that no specific anticoliform substance was present in the samples tested. It should be noted that, if an adequate separation procedure

TABLE 3.—TYPICAL VALUES FOR B.O.D. AS A FUNCTION OF SEPARATION PROCEDURE FOLLOWING PHOTOSYNTHETIC OXYGENATION

No.	Sample	Separating procedure	B.O.D., in parts per million	Percentage removal
1	Influent	None	210	0
2	Pond	No separation	195	7
3	Tailing	Settling 1 hr	105	50
4	Tailing	Laboratory centrifuging 10 min at 500 times gravity	25	88
5	Supernatant	Coagulation (followed by 30 min settling)	9	96

is used to remove algae, extensive removal of coliform as well as other bacteria should be attained.

Odors.—During the two years of operation of the pilot plants under proper conditions no odors have been observed, with the exception of a faint grassy odor which is a characteristic of the process. These observations include the all-night periods during which the pond was undergoing high loadings. When the ponds were overloaded in a deliberate attempt to break down the photosynthetic process foul odors were noticeable. These resulted principally from anaerobic bottom sludges brought to the surface during stirring. Under proper operating conditions, photosynthetic oxygenation is a process without objectionable odors.

Contaminants.—Any biological or chemical agent that interferes with the process of green algal growth may be considered a "contaminant." Chemical contaminants are those materials which may occur in sewage and are specifically toxic to algae. Although this factor has not been studied directly, indirect evidence indicates that such chemicals normally do not attain high enough concentrations in sewage to destroy the algal population.

Blue-green algae, some of which are toxic to animals, could conceivably ruin the algal cell material as a useful food product. There is little evidence of any tendency for blue-green algae to grow in fresh domestic sewage. In two years of open-air pilot-plant operation, blue-green algae have appeared only in negligible concentration.

The principal contaminants found in pilot-plant studies were green algae of the genus chlamydomonas. These organisms grow swiftly, covering the pond surface with a foamy scum in 1 or 2 days. This scum prevents light from reaching underlying strata and, hence, interrupts oxygen production. Fortunately, chlamydomonas blooms are of short duration and the organisms are easily skimmed from the pond surface by means of wind or jet skimming.

Economic Factors

Reclamation of Nutrients.—Green algae, growing in wastes, are capable of accumulating needed elements from solutions that contain these elements only in minute concentrations. Thus, green algae have great potential as agents of reclamation. For example, in growth-unit experiments algae growing in sewage were supplied a small excess of carbon dioxide. As a result, all but a trace of ammonia nitrogen was incorporated in algal cell material. If a culture is supplied air containing 0.03% CO_2, from 60% to 80% of the sewage nitrogen is fixed in algal cell material within a few days. Similar reclamation of other critical elements occurs. These facts indicate that photosynthesis for waste reclamation may have intrinsic values to the national economy over and above its usefulness as a sewage treatment process. This may be further understood when it is considered that sewage is not truly a waste. Derived from the most nutritive photosynthate harvested from the land, sewage contains the low energy forms of every element critical to life. Nitrogen might be cited as a typical example. Nitrogen is essential in the human body and yet if a daily nitrogen balance were made on a normal human subject, it would be difficult to demonstrate any significant utilization of nitrogen because the amount excreted would be found to be almost identical to the amount consumed. Only the form and energy level of the nitrogenous compounds would be changed. Living animals are thus in dynamic equilibrium with their environment, and the amounts of critical elements permanently affixed in their bodies are negligible when compared with the total amounts which are consumed and excreted during their lifetime. Thus excreted, organic matter has undergone little more than a reduction in its chemical energy content, and it would be surprising if it were not an ideal medium for algal growth.

Mention should be made also of some of the possibilities of this process for water reclamation. For example, the quantity of water required to produce a pound of protein by this process can be computed to be less than 1/100th of that required to produce a pound of protein by conventional agricultural methods. This difference is mainly due to the relatively high photosynthetic efficiency of the process. When coagulation is used for algae removal, effluents are of high quality and there does not appear to be any technical reason why they could not directly supplement a water supply if first processed by sand filtration and chlorination.

Algae as Food and Raw Material.—Results of investigations[9] have indicated the value of algae as a food and as a source of industrial raw materials. Sewage-grown algae have been fed satisfactorily to a number of animals with no evidence of toxic effects. One group of chicks received dried sewage-grown algae as their sole source of protein. Gain in live weight of these chicks average 4.2% per day. This may be compared with a maximum gain for chicks of approximately 8% per day obtained with a protein mixture considered ideal. From this, as compared with vegetable protein, the value of sewage-grown algae as a chicken feed supplement should be approximately $100 per ton.

In tropical areas of the world, which receive much solar energy but which often lack fixed nitrogen and other essential elements for food production, it is possible that the photosynthetic process could be applied to recycle these elements, thereby greatly increasing the food supply.

The fuel characteristics of dry algae are similar to those of medium-grade bituminous coal although their heat content is somewhat less, ranging up to 10,000 BTU per pound. For a few more years, however, the food value of dry algae will probably be its greatest economic value.

The high protein content—more than 50%—is not the only important quality of algae. Algae may become an important source of vitamins, or of starting products for organic synthesis, or as organic collectors of elements such as germanium, which algae concentrate. Exploration of these possibilities has been seriously restricted by a lack of algae with which to experiment. It is possible that one or more of these uses could at once make sewage treatment by photosynthesis an economically feasible process.

Plant Costs.—No attempt will be made to present detailed estimates of the cost to build and operate a plant to treat sewage by photosynthetic oxygenation. The cost of each plant where the process might be used must be evaluated specifically in accordance with the design principles set forth. It does appear that the total cost for a plant to grow algae would be less than that for conventional secondary treatment when the cost of land is not excessively high. The development of economical methods of harvesting the yield of from 1 ton to 1.5 tons of algae that can be grown per million gallons of sewage might bring the actual cost much below that of conventional treatment because of the value of the harvested algae.

Summary and Conclusions

Oxidation ponds are classified in accordance with the principal source of oxygen. Type 2 ponds in which oxygen is produced essentially by photosynthesis can be much smaller than ponds of Type 1 in which the necessary oxygen is supplied primarily by surface aeration.

Basic rational formulations for pond detention periods and pond depths are derived by utilizing the law of conservation of energy together with solar energy data and data on the light-transmitting characteristics of algal cultures. The application of these formulations to design of Type 2 ponds is illustrated and discussed. When design criteria are correctly applied, photosynthetic oxygenation will result in sewage treatment equivalent to complete treatment achieved by other methods.

Successful technical design of a plant for the photosynthetic oxygenation process requires consideration of the influences of such variables of light, temperature, and sewage quality on symbiotic bacterial and algal growth. Although the interrelationship between these variables is complex, when applied to algal growth their effects can be conveniently incorporated into design equations as coefficients. No firm value can be assigned to the over-all photosynthetic efficiency because of the modifying effects of environmental factors which are largely unknown. For the present, a value approaching 0.1 can be attained in experimental work whereas values exceeding 0.20 do not appear likely because of the limited ability of algae to utilize light of high intensity.

Before photosynthetic oxygen production in Type 2 ponds can attain its maximum potential as a practical form of sewage treatment, economical methods for algal separation must be further evaluated, developed, and demonstrated.

The technical feasibility of photosynthetic oxygenation in sewage treatment may be considered an accomplished fact. The reclamation of animal food from sewage in the form of algae appears highly promising, but practical attainment will be deterred pending further investigation of separation procedures. More studies of photosynthetic efficiency, separation of algae from cultures, and of other factors are necessary—particularly of the value of the algal cell materials produced in the process.

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DISCUSSION

ISADORE NUSBAUM,[19] A.M. ASCE.—In the past decade much interest has developed in the use of oxidation ponds for the treatment of liquid wastes from small and moderate-sized communities, institutions, military establishments, and industry. As a result of increased construction and operating costs for conventionally designed sewage treatment works, the use of oxidation ponds has been presented as a means of attaining a high degree of treatment at low cost. The use of oxidation ponds for the treatment of sewage has now become extensive, particularly throughout the southwest and far west regions of the United States; yet only few empirical data are available for their design. The authors have presented basic data on the role of photosynthesis in sewage treatment. Much remains to be clarified before the fundamental data available through the study of phytoplankton can be used for the realistic design of a sewage treatment plant.

Until this work is complete, frequently used deviations from the present empirical data, such as organic loadings of 50 lb of B.O.D. per acre of surface area per day, minimum depths of from 3 ft to 4 ft, and minimum detention periods of 30 days, must be viewed with caution. This attitude should not discourage any community from including in the pond arrangement such flexibility that these characteristics might be varied in the interest of obtaining pertinent data, for the area and waste involved, upon which to base extensions and operating practice.

The authors have divided oxidation ponds into two rather artificial classifications: Type 1 ponds are those which, by the authors' definition, obtain the oxygen necessary for waste stabilization through surface reaeration and have detention periods of from at least three weeks to six weeks. Type 2 ponds are those which have detention periods of less than one week and which are highly dependent on photosynthesis for oxygen. The qualification is then introduced that Type 1 ponds may obtain large amounts of oxygen through photosynthesis when conditions are favorable. A brief analysis of the situation demonstrates that photosynthesis, or causes other than surface reaeration, must be responsible for the stabilization which takes place in the many hundreds of oxidation ponds now in use in the southwest and which are characterized by the authors as Type 1 ponds. The rate at which oxygen is transferred from the atmosphere to a water media through the air-water interface depends on several factors, but primarily on the extent of the dissolved-oxygen deficit in the water. If the water is saturated or supersaturated with oxygen, there is no net transfer of oxygen from the atmosphere and indeed there may be a loss of oxygen from the water to air. The upper 12 in. or more of conventionally designed ponds are frequently supersaturated with oxygen only for short periods, principally during hours of darkness, and have oxygen concentrations appreciably below saturation. A typical example of such variation is pictured by D. F. Smallhorst, B. N. Walton, and Jack Myers.[20]

[19] Senior Water Pollution Control Engr., San Diego Regional Water Pollution Control Board, San Diego, Calif.

[20] "The Use of Oxidation Ponds in Sewage Treatment," by D. F. Smallhorst, B. N. Walton, and Jack Myers, *Manual for Sewage Plant Operators*, Texas Water & Sewage Works Assn., 1955, Chapter XIII.

The amount of oxygen which may be transferred through the air-water interface is limited by the characteristics of the pond itself. For example, Karl Imhoff and G. M. Fair[6] state that for ponds approximately 3 ft in depth the rate of reaeration from the atmosphere at 100% oxygen deficit is 13 lb of oxygen per acre of surface area per day. This condition rarely exists, and for the more realistic mean limiting condition of a 20% oxygen deficit in ponds designed for loadings of 50 lb of B.O.D. per acre of surface area per day, the atmosphere would supply 3 lb of oxygen per acre per day. It is quite evident that a deficit of 47 lb of oxygen per acre per day would exist, together with an extremely offensive anaerobic condition, unless oxygen for aerobic microbial action were supplied by other means. Experiences in southern California and Texas have shown that at the 50-lb B.O.D. loading oxygen concentrations in the ponds are extremely favorable throughout the year.

Although pond loadings are conveniently computed in terms of available surface area, depth plays an important part in the satisfactory operation of an oxidation pond. It is necessary to maintain at least 3 ft of water in the pond in order to avoid the growth of nuisance vegetation. Messrs. Smallhorst, Walton, and Myers[20] have pointed out that temperatures in very shallow ponds may become too high during the summer to permit the growth of algae such as chlorella. Depth through the larger-volume plant also permits the retention of greater quantities of oxygen during periods of supersaturation. Although the bottom layers may be anaerobic in deeper ponds, this factor may contribute to the over-all reduction of B.O.D. which occurs. Otherwise all the carbon dioxide produced by aerobic bacteria from the organic matter in the waste might be used by the algae in the resynthesis of organic matter. Increased depths also permit the rapid dispersion of the incoming waste, thus avoiding shock loading effects and minimizing the resuspension of solids from the bottom of the pond.

Recirculation has been found to have a distinctly salutary effect on the operation of both ponds and the entire sewage treatment plant. Offensive odors surrounding some treatment works have been entirely controlled by the recirculation of pond effluent. Where the sewage is given some secondary treatment before it is discharged to the pond, the secondary units have been found to function with fewer problems when recirculation is practiced. The most important effect of recirculation is to reduce the shock loading of high-B.O.D. wastes on the pond.

The writer has observed the operation of many oxidation ponds in southern California and doubts that the shallow, short-detention-period ponds proposed by the authors will withstand the intermittent high loadings that occur unless some form of recirculation is practiced or the ponds are merely used as a final treatment following secondary treatment.

The amount of recirculation to be used has never been determined except by trial-and-error methods. Messrs. Smallhorst, Walton, and Myers[20] have recommended that provisions for recirculation of the effluent be included in plants utilizing oxidation ponds and that recirculation ratios of from 15% to 50% should prove satisfactory. The writer believes, based on his experience, that recirculation ratios of at least one part pond effluent to two parts of sewage flow should be provided and should be necessary for recirculation, particularly where primary effluent is discharged to the ponds. It appears likely that the amount of or necessity for recirculation depends on the initial oxygen requirement of the waste.

Aerobic bacteria are necessary inhabitants of oxidation ponds because it is by their action that organic matter in the wastes is destroyed or converted to carbon dioxide to be used by the phytoplankton. Algae have been cultivated in synthetic media without the presence of bacteria and extraneous organic substances. Because coliform organisms, and presumably pathogens, have shown marked reductions in numbers in passage through oxidation ponds, it has been postulated that some antibiotic or toxic substance may be generated by the algae. However, as indicated by the authors, no such change other than the normal die-off expected on storage has been observed in their experiments. The writer has found significant coliform densities in ponds with detention periods of from 10 to 15 days. Effluents from ponds with 30 days or more of detention are found to have bacterial reductions comparable to or greater than effluents from the chlorinated sewage treatment plant. Because the use of chlorination in small sewage treatment works is usually quite ineffective due to insufficient operation and maintenance, oxidation ponds have been used to produce bacterially safe effluents. For ponds having short detention periods, it will be necessary to provide some means of chemical disinfection until more information is available on any bacterial hazards. However, virtually nothing is known about the disinfection of pond effluents.

Several preliminary tests have been conducted by the writer on the chlorine requirements of oxidation-pond effluents. The effluents have had low chlorine requirements of from 2 ppm to 3 ppm. The coliform population was rapidly reduced to extremely low values on chlorination in this range. The effect on the algae was undetermined, but they also may have been destroyed. If so, chlorination may decrease some of the pond effectiveness.

The authors have stated that there is little tendency for blue-green algae to grow in oxidation ponds. The presence of large numbers of blue-green algae has been reported from Texas. Also, in the San Diego (Calif.) area two separate ponds, thirty miles apart, have been afflicted with an almost pure culture of blue-green algae of the genus arthrospira. The vegetative cells of these organisms are found in free-floating filaments which are helical in shape. Apparently, organisms rising to the surface collect in small clumps which then are driven by the wind into pockets where large mats of the arthrospira accumulate. As the surface of the mats putrefies, an extremely foul, offensive odor is produced.

Nevertheless, the effluent from these ponds was well treated. Some investigational work has indicated that the growth of these specific algae is connected with the salinity of the ponds involved. The arthrospira have previously been found in ponds of brackish water. Both the infested ponds have sodium chloride concentrations of approximately 3,500 ppm; in one case, this was because of saline ground-water infiltration and in the other because a slough with no outlet was being used as the pond.

As reported in an earlier paper[11] the total inorganic solids content of the sewage used for these experiments, conducted at the Sanitary Engineering Research Laboratory of the University of California, is quite low. Data are lacking on the use of ponds in areas where the normal solids content of the water is high. It is true that synthetic media for the culture of algae are high in mineral solids; however, such media have been carefully prepared to produce optimum growth.

There is some evidence[21] to indicate that relatively small changes in chloride concentrations may have definite effects on the cultivation of certain phytoplankton. The City of Oceanside (Calif.) has experienced difficulties with an experimental oxidation pond having a surface area of 5 acres. The oxidation pond contains between 800 ppm and 1,000 ppm of sodium chloride because of the high salinity of the community water supply. Many other factors may be involved and some have been investigated with no positive results. Attempts to seed chlorella into one of the brackish ponds mentioned earlier were completely unsuccessful.

R. W. Krauss[22] has pointed out that much work remains to be done on the total nutrient requirements of algae grown in mass culture and that, even in complex organic media with large numbers of compounds in solution, it is possible that growth may be limited by the absence or unavailability of some element. Iron, zinc, copper, molybdenum, manganese, cobalt, and other elements are believed to be essential micronutrients for the cultivation of algae. It is quite conceivable that, despite the heterogeneous makeup of sewage in some regions, the sewage may be deficient in some element necessary for a vigorous, healthy growth of algae.

Few data have been found on the effects of insecticide formulations on the operation of oxidation ponds. Ponds do, under some circumstances, harbor mosquito and gnat larvae, and health departments justifiably demand that insect control be exercised. In at least two cases with which the writer is familiar, the spraying of ponds with diesel-oil solutions of DDT were followed by almost complete algal inactivity. Much less impairment was suffered when a water-type emulsion of lindane was used.

Despite the lack of knowledge about many aspects of the use of oxidation ponds for sewage treatment, they do serve a useful purpose in sanitary engineering. The limited information has undoubtedly resulted in lower efficiencies than might otherwise be possible.

The use of oxidation ponds for sewage treatment must be justified principally on their effectiveness and their cost for that specific purpose. The recovery of valuable by-products other than water for agricultural or industrial purposes is in an elementary stage of development and does not yet merit consideration in the design of oxidation ponds for sewage treatment.

William J. Oswald,[23] A. M. ASCE, and Harold B. Gotaas,[24] M. ASCE.—Mr. Nusbaum's remarks concerning conventional oxidation ponds commonly used for sewage treatment in the western and southwestern United States indicate concern regarding any deviation from the present empirical design

[21] "Relative and Limiting Concentrations of Major Mineral Constituents for the Growth of Algal Flagellates," by Luigi Pravasoli, V. V. A. McLaughlin, and I. J. Pinter, *Transactions*, New York Academy of Sciences, Series II, Vol. 16, 1954, p. 412.

[22] "Nutrient Supply for Large-Scale Algal Cultures," by R. W. Krauss, *Scientific Monthly*, Vol. 80, 1955, p. 21.

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criteria: Organic loadings of 50 lb of B.O.D. per acre of surface area per day, minimum depths of from 3 ft to 4 ft, and minimum detention periods of 30 days. Actually there has been very little scientific analysis or investigation on which to base these criteria. They were proposed and used before photosynthesis was given particular consideration as a source of oxygen for bacterial decomposition. The early oxidation ponds were designed on the basis that oxygen would be supplied by surface aeration from the atmosphere and detention periods were determined on the basis of what experience had indicated would provide satisfactory removal of B.O.D. without the creation of nuisances. The ponds were designed sufficiently deep to prevent penetration of light to the bottom, thus inhibiting the growth of nuisance vegetation. Oxidation ponds can be operated over a wide range of conditions and still provide a reasonably satisfactory effluent.

The writers indicated two types of oxidation ponds: Type 1, depending primarily on surface aeration as the oxygen source with oxygen from photosynthesis coincidental but not essential in the maintenance of aerobic conditions, and Type 2, depending primarily on photosynthetic oxygen sources. Naturally there is no fine line of demarcation because these types are the two extremes. As indicated in the paper, long-detention-period oxidation ponds may receive considerable oxygen produced by algae growing near the pond surface. Mr. Nusbaum's value of 47 lb of oxygen per acre per day could easily have been produced by photosynthesis; in fact, oxygen is produced at many times this rate in Type 2 ponds. Although some oxygen may be produced photosynthetically in the conventional pond, it should be emphasized that the two types of ponds are very different. The conventional Type 1 ponds treat the waste at a low rate, requiring a relatively small quantity of oxygen per acre and often have sludge deposits on the bottom which decompose anaerobically. The high-rate Type 2 ponds, however, may treat wastes at ten times the conventional rate, developing dense algal cultures which supply nearly all the oxygen requirements for the maintenance of aerobic conditions throughout. The purpose of photosynthetic oxygenation is to treat the waste more rapidly on a smaller area while developing sufficiently dense cultures of algae to permit harvesting and reclamation of many of the valuable nutrients in the waste.

Conventional oxidation ponds designed for a B.O.D. loading of 50 lb per acre per day and a 30-day detention period often contain a sludge deposit on the bottom which undergoes anaerobic decomposition. Much of the dissolved and colloidal organic matter of the sewage is flocculated and settles to the bottom. If aerobic conditions are maintained in the upper part of the pond water, only the B.O.D. of the nonsettling material and the residual B.O.D. of the anaerobically decomposed sludge are satisfied aerobically. Thus, less oxygen is required than if all the organic matter were decomposed aerobically. If the anaerobic sludge deposits are not too large, odor and nuisance conditions are not developed because adsorbed atmospheric oxygen and photosynthetic oxygen in the supernatant may be sufficient to prevent odor nuisances. It may be seen that the average B.O.D. loading per acre per day is an inaccurate parameter because the amount of deposition and anaerobic decomposition of

B.O.D. may be greater than the aerobic oxidation and the algal oxygen production may vary widely depending on sunlight and other factors.

Oxidation ponds may be operated with detention periods and loadings between those of conventional Type 1 practice and values shown for the Type 2, high-rate ponds. The Type 2 pond requires some vertical mixing to keep the sludge, the bacteria, and the algae in close proximity so that the sludge will be aerobic and the algae can obtain the carbon dioxide and ammonia released by the bacteria. The writers have been able neither to develop dense algal cultures in deep, long detention period ponds nor to find any conventionally designed ponds which produce high algal concentrations. There is a valid physical reason for this which was presented as Eq. 12. This equation shows that algal concentrations exceeding 40 ppm cannot be sustained in ponds 3 ft deep. Algal densities greater than 25 ppm are rare in the conventional pond, compared to densities of from 200 ppm to 350 ppm in the Type 2 pond when ample sunlight and nutrients are available.

Studies indicate that the Type 2 high-rate ponds will have the greatest economic possibilities when high-quality secondary treatment is desired. Pilot-plant experience indicates that an effluent is produced from which 95% to 97% of the B.O.D. has been removed.

Mr. Nusbaum refers to the desirability of recirculation for overcoming shock loads on the pond. The operation of the high-rate pond requires recirculation for seeding the influent waste with algae and adding oxygen initially to provide aerobic conditions. However, recirculation is desirable in the operation of any oxidation pond. In the Type 2 pond, the amount of recirculation should be controlled because extensive recirculation hastens bioflocculation and settling of organic matter. Separation of the bacteria and nutrients from the algae which do not settle retards algal growth.

Reference was made to the die-away or removal of coliform bacteria in high-rate oxidation ponds. If the algae are chemically coagulated and precipitated, practically all the coliform organisms are removed to the sludge, and the effluent may be satisfactorily filtered through a rapid sand filter. Many observations of the change in coliform densities in the high-rate oxidation ponds have shown that the most probable number decreases from 10^7 or 10^8 in the sewage to between 10^2 and 10^4 in the pond effluent. The variation between 10^2 and 10^4 is affected by the detention period and the depth. Ponds of shallow depths and longer detention periods in intense sunlight show lower coliform counts in the effluent.

Mr. Nusbaum indicated that oxidation ponds have low chlorine requirements of 2 ppm to 3 ppm. The writers have found that the effluents from Type 2 ponds have a high chlorine demand due to their high algal concentration. They have also found that the effluent from Type 2 ponds, after harvesting the algae, has a very low demand. This indicates, therefore, that the pond effluents referred to by Mr. Nusbaum contained very few algae, and hence probably obtained little oxygen from photosynthesis.

The writers are unable to answer completely the question of blue-green algal development in long-detention-period ponds and the lack of such development in high-rate ponds. There are several factors which may influence the development of the blue-green algae. First, blue-green algae seem to grow better in partly nitrified sewage than do green algae, but appear unable to compete with green algae when ammonia nitrogen, rather than nitrate nitrogen, is the nitrogen source. Only ammonia nitrogen is available in the short-detention-period ponds. Secondly, blue-green algae will grow when sewage nitrogen is low or absent because they have the capacity to fix nitrogen from the air. There is usually an excess of nitrogen in high-rate ponds. Inasmuch as blue-green algae often grow around mats of organic sludge, which may rise from the bottom of the pond where a sludge blanket has developed, they may require longer detention periods than green algae. It is therefore believed possible that the detention periods of the Type 2 pond may be too short for growth of blue-green algae, permitting only fast growing green algae to develop on the available nutrients.

Mr. Nusbaum has raised the question of growing chlorella and other algae in ponds high in sodium chloride or total solids. There is little information indicating that brackish waters influence algal growth when total salt concentrations are less than 3,000 ppm and no toxic minerals are present. It is possible that the noted unsuccessful results of attempts to seed chlorella into brackish ponds were due to insufficient seed or excessively long detention periods. Because chlorella are small, rapidly growing algae, they dominate when detention periods are short, and other larger, more slowly growing organisms do not have the opportunity to overgrow them. Chlorella, scenedesmus, and other small, rapidly growing cells seldom predominate when the detention period is long.

Much additional study of photosynthetic oxygenation of sewage and of separation of the algae from the liquid has been accomplished since the paper was written. Pilot-plant investigations have shown that the algae and other suspended and colloidal matter can be continuously precipitated, and an effluent can be produced that contains a very low B.O.D. and bacteria count. The investigations indicate that during summer weather considerably more than one ton, dry weight, of algae can be produced per million gallons of average domestic sewage. Based on pilot-plant studies, the cost of growing, separating, and drying the algae while also providing a high-quality effluent is believed to be less than $100 per million gallons for average conditions. The algae contain from 45% to 55% protein as well as carbohydrates, fats, and minerals, and have an indicated value of more than $100 per ton as an animal food. Hence, even though this process is now only in the developmental stage and accurate cost and operational data for a full-scale plant are not available, it seems probable that Type 2 short-detention-period ponds and algae harvesting may provide high-quality sewage treatment for a very low net cost. The most economical use of the process may be for cities requiring complete, year-round sewage treatment in areas where the climate and sunlight are satisfactory. This would generally be in areas between the equator and 35° latitude. The process may also be economical for use during the summer in places farther from the equator where only partial treatment is necessary during the cold winter period.

A rational formulation was presented of the major fundamental biological, physical, and chemical factors that govern the production of oxygen and algae in sewage ponds together with engineering applications of these fundamentals. These principles are applicable under a wide variety of conditions and can be utilized in the design of either conventional or high-rate type ponds whenever photosynthesis is considered as a source of oxygen. Naturally, caution should be exercised in designing high-rate ponds of large magnitude until the process has been operated at plant-scale installations. Present information indicates, however, that conventional detention periods and loadings can be changed for greater efficiency and economy. Future designs of conventional oxidation ponds should include provision for conversion to high-rate operation, a step which is essential for the development of sufficient algae to permit economical harvesting and reclamation.

Pilot-plant experience with this process indicates the possibilities for much more extensive reclamation of the valuable nutrients now being wasted in costly treatment processes. The high-rate process, which utilizes sunlight as a source of energy for growing algae to treat wastes and to reclaim nutrients, has one less degree of freedom for general application than the more conventional processes because of light requirements. However, in many localities sunlight is an unusually abundant item and it is unwise to waste either nutrient materials or sunlight if a process can be developed for their economical utilization. Engineered control of photosynthesis offers a means to this end. Certainly civilization might have been retarded if engineers had chosen to allow natural processes to proceed only at their primordial rate.