for development of the interface controller from which this foam control device was adapted.

SUMMARY

This paper describes the construction and operation of an electronic foam controller suitable for use with fermentation vessels. Details are given of a complete foam control system making use of the electronic controller for the control of fermentations of the aerobic type in which large quantities of air are dispersed, and large amounts of electric energy are dissipated.

The electronic foam controller operates at low electrode voltage, and is simple and easy to construct. Components are readily available. The controller is actuated when foam in the fermentor touches an insulated electrode, and small increments of antifoam agent are then admitted as permitted by a timer.

The controller may be used for other purposes, such as level control, or interface control in liquid-liquid systems. By incorporating several sensing and activating circuits into the controller, it may be used to perform several functions simultaneously.

REFERENCES

ECHEVARRIA, J. 1955 Foam control improves fermentations. Chem. Eng., **62**, No. 4, 212.

EDWARDS, M. L. 1946 Foam reducer. U. S. Patent 2,401,469, June 4.

GORDON, W. O. AND VELDHUIS, M. K. 1953 Controlling foam in submerged and aerated propagation of microorganisms. U. S. Patent 2,635,070, April 14.

HERSH, R. E., FRY, E. M., AND FENSKE, M. R. 1938 Liquid-level control apparatus. Ind. Eng. Chem., **30**, 363-364.

HUMFELD, H., AESCHLIMANN, E., AND HOFFMAN, J. R. 1952 Fermentor with rotating foam-breaking vanes. U. S. Patent 2,610,155, Sept. 9.

NAUCLER, J. O. 1948 Defrothing apparatus. U. S. Patent 2,446,717, August 10.

STEFANIAK, J. J., GAILEY, F. B., BROWN, C. S., AND JOHNSON, M. J. 1946 Pilot-plant equipment for submerged production of penicillin. Ind. Eng. Chem., **38**, 666-671.

Anaerobic Digestion of Algae

C. G. GOLUEKE, W. J. OSWALD AND H. B. GOTAAS

Sanitary Engineering Research Laboratory, Department of Engineering, University of California, Berkeley, California

Received for publication September 4, 1956

Stabilization lagoons, in which secondary treatment of waste waters is accomplished through the combined activities of bacteria and algae, are being used extensively, especially as a substitute for more complex and expensive methods. In the lagoons, bacteria primarily decompose the organic constituents of the wastes, making them available to the algae. The algae, by way of photosynthesis, release oxygen which, in turn, is used by the bacteria to oxidize the wastes. Whenever photosynthesis is utilized for oxygenation in waste treatment, ultimate disposal of the algal cell material, produced simultaneously with oxygen, may require further processing.

In low-rate deep lagoons in which the approximate treatment rate is less than 30 lb of 5-day BOD per acre ft per day (Caldwell, 1946; Van Huvelin and Svore, 1954), the disposal problem is either minor or nonexistent, since algae are in concentrations rarely exceeding 20 mg per L. Many of the algae in these lagoons are consumed by planktonic phagotrophs such as *Daphnia* or *Cyclops*, or slowly settle and become part of the complex at the lagoon bottom. Much of this settled material is consumed by *Chironomas* larvae, which flourish in rich organic sediments when a small amount of oxygen is available (Kellen, 1956). In sections of the pond bottom where anaerobiosis exists, digestion occurs and algal carbon is converted into organic acids, carbon dioxide, and methane. A large fraction of the suspended algae is entrained in pond currents and is discharged into the receiving streams, where the algae serve as food for aquatic organisms. Because of their low settling velocities, unicellular algae ordinarily do not settle in streams, and hence do not immediately become part of stream-bottom deposits. Natural processes thus solve the problem of algal disposal in low-rate ponds, excess carbon, nitrogen, and energy being dispersed into the atmosphere and waters.

In high-rate shallow lagoons, sewage may be applied at several times the rate used in low-rate lagoons, and photosynthesis is practically the sole source of oxygen for aerobic biologic decomposition of wastes. Algal concentrations frequently reach 400 mg per L. Because of the high concentrations of algae characteristic of this process, suitable provision must be made for the ultimate disposal of the algal crop. If permitted to settle, the algae become a part of the bottom deposits and ultimately die. The algal debris then undergoes fermentation, and substances toxic to algae, such as H_2S, are produced. In addition, rising gas resulting from active fermentation brings about an increase in lagoon turbidity by resuspending the bottom deposits. Because the increased turbidity curtails available light energy, algal development is retarded. Thus, it becomes apparent that prevention of excessive bottom anaerobiosis due to algal decomposition is important to the most satisfactory operation of high-rate lagoons. Discharging large concentrations of algae into a receiving stream or lake can be objectionable under some conditions. Although algae do not settle at normal stream velocities nor readily die and undergo decomposition, nevertheless in large concentrations they can deplete stream oxygen reserves at night. Such depletion is harmful to fish and other wild life in the stream, and therefore must be avoided. The alternative to discharge of excessive concentrations of algae into the streams or lakes is to maintain the algae in suspension during the growth process, and to provide for their separation. Once algae are removed, the supernatant retains only a very limited amount of biologically oxidizable organic matter, and it thus becomes a desirable stream additive.

The process of producing algae in high-rate shallow ponds has been described in several publications (Gotaas and Oswald, 1954; Oswald and Gotaac, 1955). Several methods of separation have been developed recently, at least one of which appears economically feasible at this time. Results of studies conducted by Grau on the Davis campus of the University of California in 1955 and other evidence (Fink *et al.*, 1954) indicate that the high value of the harvested algae as an animal food supplement will normally permit economic separation and reclamation.

Conditions might exist, however, under which complete processing and recovery of algae for food would not be feasible, and yet it would be desirable to remove the algae from the lagoon effluent. Under such circumstances, a readily applicable method of disposal and one which lends itself to conservation is that of controlled anaerobic digestion.

Digestion of algae to provide a source of fuel is an attractive possibility. The solar energy converted and stored by the algal cells as a result of their photosynthetic activities, can be transformed into usable energy through the anaerobic digestion of algae to produce methane. Energy is released by burning the methane.

Inasmuch as there is a need for information on problems which may be peculiar to the anaerobic digestion of algae, and because to the best of the authors' knowledge no such study has been reported in the literature, we have initiated an investigation of the anaerobic digestion of algae under the different conditions to be described in this paper.

Materials and Methods

Inasmuch as some of the terms commonly used by sanitary engineers with reference to certain phases of the digestion process may be unfamiliar to readers specializing in other fields, such terms are defined as follows: The term *digester* may refer either to the digesting culture or to the culture plus the vessel containing it. Used as a noun, *feed* is synonymous with *nutrient source;* as a verb, it means to add nutrient source to the culture. *Loading* refers to the total amount of nutrient source given the digester each day. *Detention period* determines rates of the process and is defined as $D = V/Q$ where D is detention period in days, V is the volume of the digester, and Q is the displacement volume per day.

The study on the digestion of algae was carried on in five series of experiments. In the first series, which consisted of two separate groups of experiments, an estimate was made of the comparative values of algae and of raw sewage sludge as sources of nutrients. Digester performance at mesophilic and at thermophilic temperatures was the subject of the second series of experiments. The third series involved a determination of the effect, if any, of using alum-flocculated algae as feed. The fourth series dealt with the effect of detention period and the solids concentration of the nutrient source. The reaction of the digesters to two loading programs was the subject of the fifth and final series.

The digesters were set up and operated as follows: Eleven liters of digesting algal sludge or raw sewage sludge were placed in each of two 20-L pyrex jars. As is shown in figure 1 the jars were equipped with suitable collecting devices for gas, and pumps for injecting feed and circulating and withdrawing digested sludge. The digesters were placed in insulated cabinets in which temperatures were maintained at 30 C (±1 C) in series 1, and at 50 C (±1 C) in the remaining series.

Both digesters were begun in series 1 by placing, in each of the two jars, 11 L of digesting sludge obtained from digesters operated by the local municipal sewage treatment district. In the remaining series, new digesters were not started for each succeeding experiment; instead, the old cultures were adjusted to the new conditions to be tested. Usually, a period of 2 weeks was required for this adjustment. Feeding was continued during the adjustment period. In the first group of experiments in series 1, a population of bacteria capable of attacking algal cells was built up by feeding one of the digesters a mixture consisting of equal parts of raw sludge and pure algae during the first two weeks. At the end of the second week the raw sludge was omitted. The transition to thermophilic conditions was made in series 2 by increasing the temperature of the digesters to 50 C at increments of 5 C each third day.

The digesters were fed once a day, and an equal quantity of sludge (mixed liquor) withdrawn directly before feeding. With the exception of series 5, in which loading was varied, the amount of nutrient added each day furnished 0.09 lbs of volatile matter per cu ft of

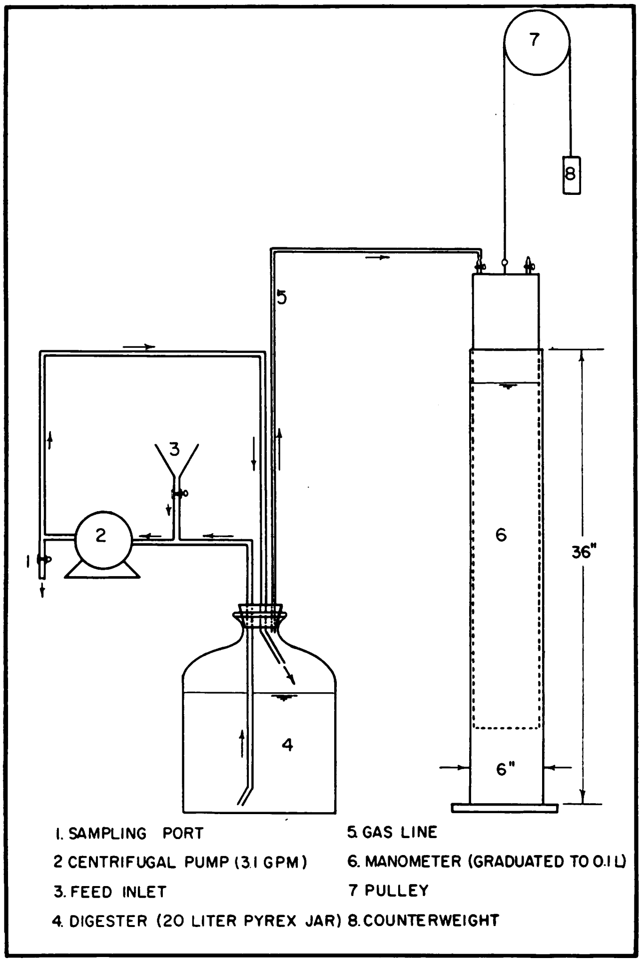

FIG. 1. Schematic drawing of a complete digester unit, including inlet port for feeding, outlet port for sampling, and gas plenum for collecting gas. The plenum consists of two tubes of Lucite, one telescoping into the other. A solution of HCl (1 per cent) acts as a seal to prevent the escape of gas.

digesting culture. Volume of nutrient source added each day was adjusted to result in a detention period of 30 days (that is, 367 ml of nutrient source per day) in all experiments other than those in series 4 in which detention period was the variable tested. Raw sludge, used as a source of nutrients, was obtained from the local sewage treatment plant. Algal feed was obtained either by centrifuging, or by flocculating with alum, effluent from oxygenation ponds operated for algal growth studies. The algal culture, consisting principally of *Scenedesmus* spp. and *Chlorella* spp., usually was concentrated to a paste having 15 per cent solids, and then diluted with water in a Waring Blendor to a slurry having a solids content of 8 to 9 per cent. Total nitrogen content of the algal sludge varied from 6 to 8 per cent of the total solids. Approximately 3 per cent of the nitrogen was in the form of ammonia. Approximately 4 per cent of the total solids in the alum-flocculated algal feed was in the form of aluminum. Analyses of the algal feed indicated a variation in volatile acid content from 300 to 600 mg per L.

Total volume of gas produced was determined prior to feeding. The gas was analyzed by means of a Fisher gas analyzer. Volatile acids were extracted by liquid-liquid ether extraction and are expressed as acetic acid in mg per L of sludge.

In series 1 and 2, estimates of quality of digester performance were based on rate and extent of destruction of volatile matter, gas produced per lb of volatile matter introduced, and nature of the digested sludge. Because experience gained in previous experiments indicated its validity, daily gas production and the volume of gas produced per lb of volatile matter introduced were used as indicators of activity in series 3, 4, and 5.

RESULTS

Raw sewage sludge compared with algae as a source of nutrients. As is shown in table 1, the volume of gas produced per lb of volatile matter destroyed by digesters A (raw sludge) and B (algae) was comparable, namely, 16.3 cu ft for A and 15.8 cu ft for B. Gas production per lb of volatile matter introduced was quite different, however, in that gas production by B was consistently 2 to 4 cu ft less than that produced by A [figure 2 (1)]. This difference in gas production per lb

TABLE 1. *Destruction of volatile matter and production of gas as a result of anaerobic digestion under various conditions*

Digester					Gas Production (Average)		Per Cent of Total Gas Production (Volumetric Average)			
Series	Detention period	Material	Temp	Destruction of volatile matter	Volatile matter introduced	Volatile matter destroyed	CO_2	CH_4	H_2	N_2 and others
	days		*C*	%	*cu ft/lb*	*cu ft/lb*				
1	30	Raw sludge	35	57	9.2	16.2	30.9	61.4	2.4	5.3
1	30	Raw sludge	35	60	9.9	16.3	31.3	62.5	2.1	4.1
1	30	Algae	35	36.4	6.1	15.8	31.9	60.9	1.0	6.2
1	30	Algae	35	43.1	7.0	16.1	32.3	61.3	0.9	5.5
2	30	Algae	35	44.3	6.4	14.4	32.3	62.4	2.2	3.1
2	30	Algae	50	54.0	8.0	15.0	32.3	62.1	2.3	3.3
3	30	Algae	50		7.9		32.4	62.1	1.6	3.8
3	30	Algae + alum	50		7.8		32.3	61.9	1.5	4.2
4	30	Algae + alum	50		8.1					
4	22	Algae + alum	50		7.9					
4	30	Algae + alum	53		8.3					
4	11	Algae + alum	53		8.2					
4	30	Algae + alum	53		8.2					
4	7	Algae + alum	53		5.4					
4	30	Algae + alum	53		8.5					
4	3.3	Algae + alum	53		4.2					
5	22	Algae + alum	53		8.4					
5	22	Algae + alum	53		8.0					

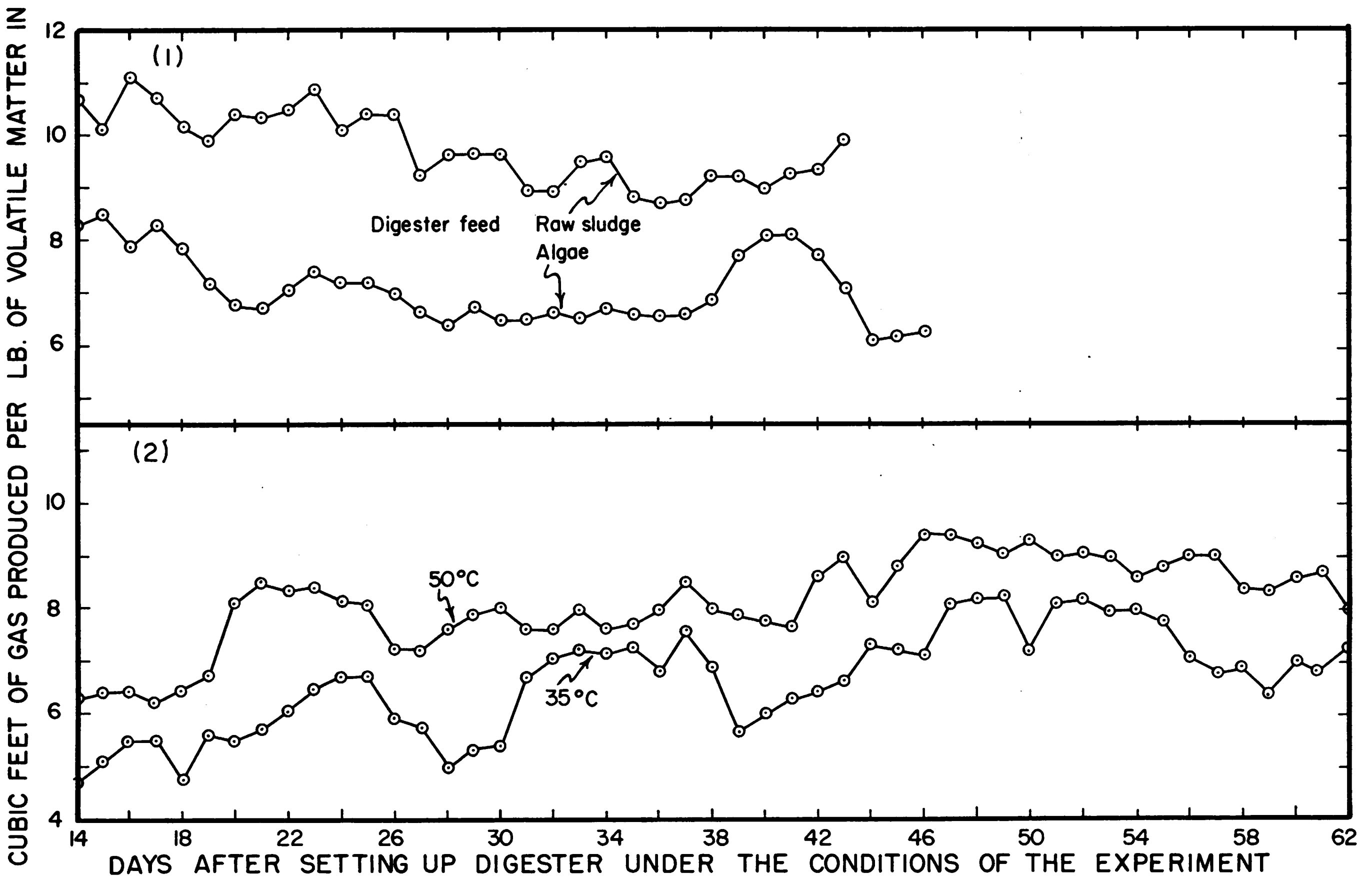

FIG. 2. The effect of nutrient source (1) and temperature (2) on gas production per pound of volatile matter introduced

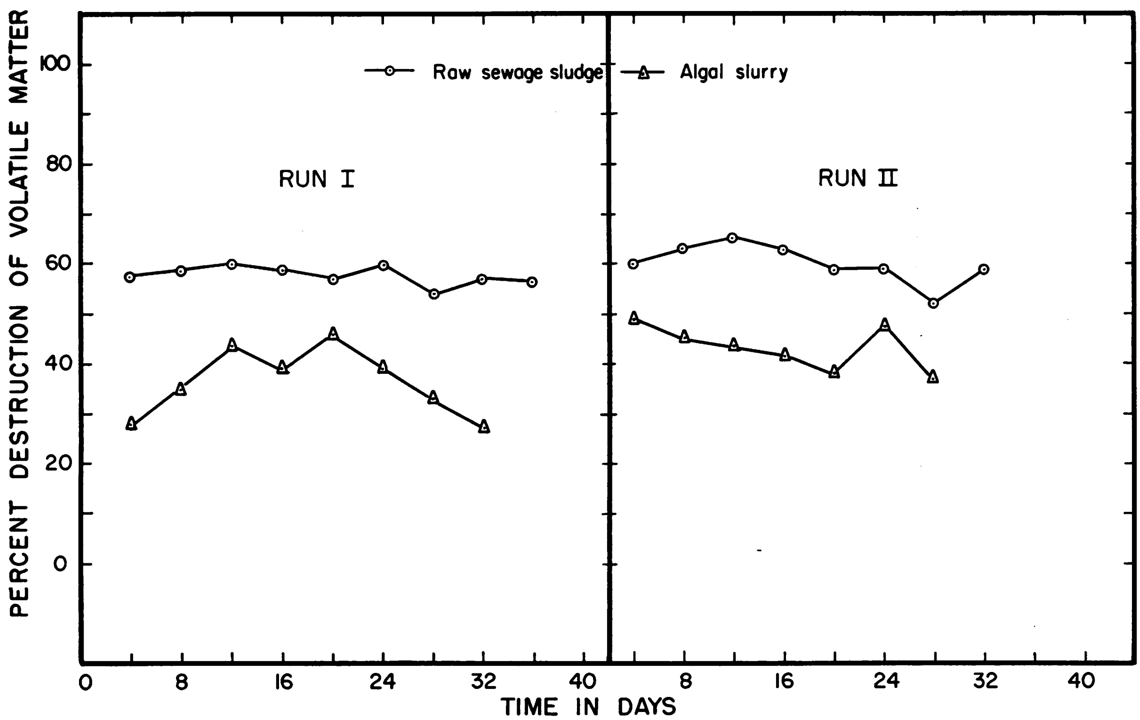

FIG. 3. Extent of destruction of volatile matter when either a raw sewage sludge or an algal slurry is used as a source of nutrients

TABLE 2. *Nitrogen and ammonia concentrations characteristic of digested sludge produced under various conditions*

Digester				Nitrogen			
				Average NH_4		Average total N	
Series	Detention	Nutrient source	Temp	Mg per L	Per cent of total N	Mg per L	Per cent of total solids
			C				
1	30	Raw sludge	35	277	2.9	7719	8.9
1	30	Raw sludge	35			1135	3.3
1	30	Algae	35	1613	56.0	2874	6.9
1	30	Algae	35	1680	47.5	3527	7.7
2	30	Algae	35	1604	61.0	3531	8.1
2	30	Algae	50	1512	67.0	2732	6.6
3	30	Algae	50	1849	66.5	2771	6.5
3	30	Algae + alum	50	1759	69.0	2539	6.3
4	30	Algae + alum	50	854	56.0	1525	5.9
4	22	Algae + alum	50	1001	55.5	1804	6.1
4	30	Algae + alum	50	670	43.5	1537	6.2
4	7	Algae + alum	50	1978	52.0	3817	6.5

of volatile matter introduced is reflected in the per cent destruction of volatile matter. As shown in figure 3, destruction of raw sludge volatile matter varied from 57 to 60 per cent; destruction of algal volatile matter, on the other hand, was never greater than 44 per cent, and did reach a low of 24 per cent. Except for hydrogen, the composition of the gas produced from both digesters was markedly similar (table 1).

Nitrogen determinations made on both sludges showed that the nitrogen concentration in sludge from B (algae) was as high as 7.7 per cent of the total solids as contrasted to 3.3 per cent in the sludge from A (raw sludge) (table 2). Volatile acid concentration in digester A (raw sludge) ranged from 351 to 402 mg per L, with pH varying from 7.3 to 7.6. Volatile acid concentration in B varied from a low of 1530 mg per L to a high of 2120 mg per L. Acids produced in both digesters were identified by paper chromatography and were found to be principally acetic acid, some propionic acid, and traces of valeric and butyric acids. The carbon content of the sludge from both digesters varied from 30 to 35 per cent on the basis of dry weight.

A comparison of the physical nature of digested sludges from the two digesters showed that sludge from B possessed less desirable characteristics than that from A. Digested sewage sludge had the gritty sediment considered to be characteristic of well-digested sludge, and it dewatered readily. Digested algae, on the other hand, was highly colloidal and gelatinous and dewatered very poorly. Sludge from digester A had a tarry odor; digested algae had an odor similar to that of fresh cow manure. Microscopic examination of the algal sludge revealed a large proportion of material as consisting of intact, green cells, although attempts to determine the viability of such cells were unsuccessful.

Thermophilic and mesophilic digestion of algae. A possible explanation of the poor performance of digester B (algae) in relation to digester A (raw sludge) could be the failure of the algal cells to die despite the adverse conditions met in a digester. Living algal cells are known to resist bacterial attack very effectively. One method of killing the algae would be by exposing them to thermophilic temperatures. Accordingly, a second series of experiments was made in which one digester (A) was maintained at 35 C, and a second (B) at 50 C. Gas production was uninterrupted in both digesters during the conditioning period. When relatively uniform gas production indicated equilibrium, data for the test were gathered.

As is shown in figure 4, gas production at 50 C was uniformly greater than at 35 C. Composition of gas, both volumetrically and gravimetrically, was quite similar at both temperatures (table 1). In both digesters CO_2 constituted approximately 30 per cent and CH_4 approximately 62 per cent of the volume of gas produced. Daily production of gas per lb of volatile matter introduced averaged 6.4 cu ft at 35 C and 8.1 cu ft at 50 C; but production per lb of volatile matter destroyed was comparable, namely, 14.4 to 15.0 cu ft [figure 2 (2) and table 1]. Destruction of volatile matter was 5 to 10 per cent greater at the higher temperature.

Nitrogen content averaged 8.1 per cent in the sludge produced at 35 C and 6.6 per cent at 50 C (table 2); ammonia constituted approximately 61 to 67 per cent of the nitrogen in both sludges. Volatile acid concen-

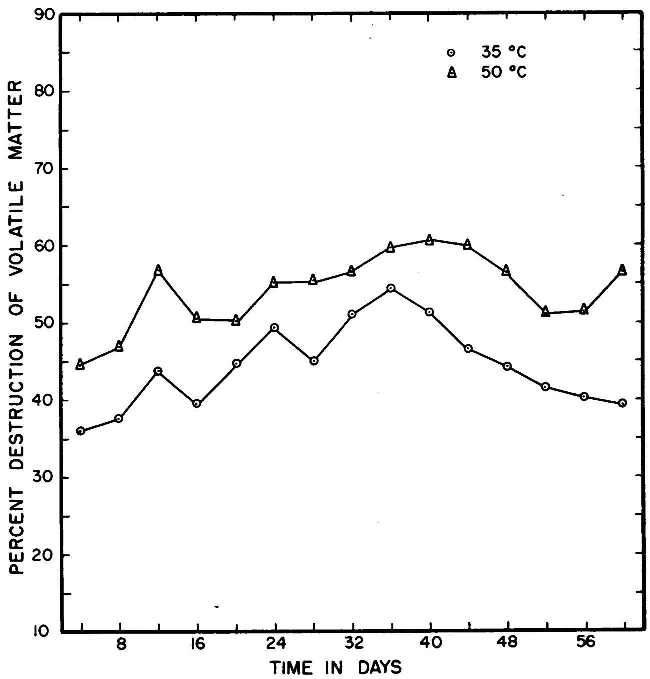

FIG. 4. Extent of destruction of volatile matter in a digester operating at 35 and at 50 C. Each point in the curves represents the average per cent destruction of volatile matter over a 4-day period.

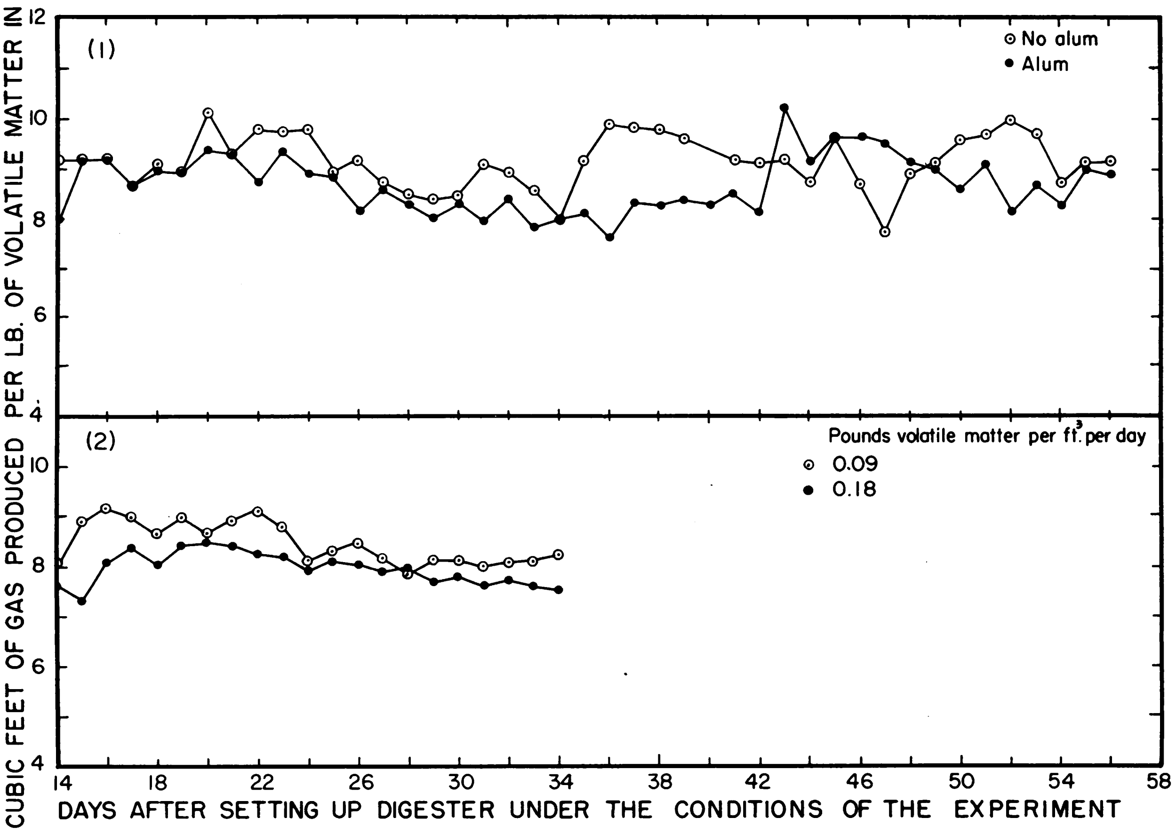

FIG. 5. (1) Effect of alum on digester activity as expressed in gas produced per pound of volatile matter introduced. (2) Effect of loading on gas production.

tration in digester A (35 C) varied from 2700 to 4080 ppm; and from 1250 to 354 ppm in digester B (50 C). Gross physical characteristics of sludge from both digesters were comparable. The emanation of ammonia from the stirred sludges was sufficiently great to make one's eyes water. Both sludges were a dull brownish green in color, although that from B (50 C) was darker. Sludge from digester B showed some improvement over that from A with respect to dewaterability, although both apparently had a high colloidal content. Microscopic examination revealed intact cells in both sludges.

Centrifuged pond algae and alum-flocculated algae as nutrient sources. Inasmuch as experiments now in progress have demonstrated that alum flocculation is an essential step in one of the most economical methods of harvesting algae, a study was made on the effect of the aluminum fraction of flocculated algae on the dynamics of the digestion process and on the physical nature of the resulting sludge.

To start the test, the contents of digester B (50 C) in the preceding experiment were divided into two equal volumes and introduced into separate digesters. The liquid volume of the digesters was increased gradually to 11 L. Digester A was fed alum-flocculated algae and the second digester (B) was fed with centrifuged pond algae.

Gas production in both digesters was practically identical, as is shown in figure 5 (1), and was comparable to that obtained at 50 C in the preceding experiment. Gas production per lb of volatile matter introduced averaged 7.9 cu ft in A, and 7.8 in B. Composition of gas was not affected by the type of nutrient source used (table 1). Computed destruction of volatile matter was almost identical in both digesters, averaging 48 to 49 per cent of the volatile matter introduced. Nitrogen content and the general nature of the sludge seemed to be comparable in both digesters (table 2).

Inasmuch as the aluminum in the flocculated algae had no apparent inhibitory effect on digester activity, and algae thus obtained were most plentiful, aluminum-flocculated algae were used as the nutrient source in all of the succeeding experiments.

Detention period. The effect of various detention periods on the digestion of algae was the subject of the fourth series of experiments. Digester A, which was maintained on a 30-day detention period, served as a control throughout the experiments. Digester B was subjected to five different detention periods, varying between 22 and 3.3 days. In all the tests, loading remained constant. When the volume of the daily ration of nutrients exceeded 500 ml, the liquid was warmed prior to introduction into the digester. In the 7.0- and 3.3-day detention period experiments, feeding and withdrawal of sludge were done twice daily, one-third of

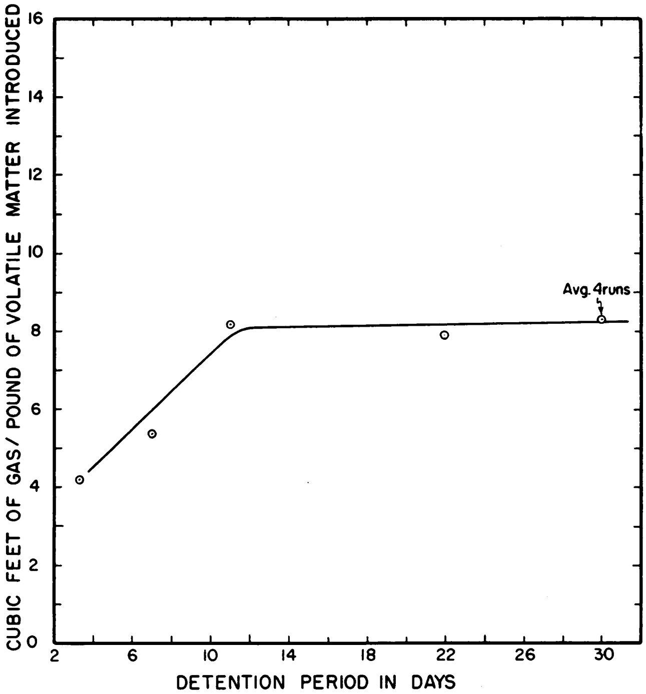

FIG. 6. The effect of length of detention period on gas production. Each point in the curve represents an average value for the daily gas production at the detention period indicated.

the total volume at 0800 hr and two-thirds at 1600 hr. Total solids concentration of the algal feed varied from 5.9 per cent for the 30-day detention period to 0.66 per cent for the 3.3-day detention period.

As is shown in figure 6, length of detention period, within the range of 30 to 11 days inclusive, had little effect on volume of gas production. At a detention period of 7 days, however, the decline was rapid in gas production per lb of volatile matter introduced. Production of gas became almost negligible during the 3.3-day detention period. According to data listed in table 2, no apparent effect on the nitrogen composition of digested sludge could be attributed directly to length of detention period within the range 30 to 7 days inclusive. Volatile acid concentration never exceeded 1200 mg per L in any of the digesters, and usually ranged from 500 to 800 mg per L. Except for the 3.3-day period, physical characteristics of the digested sludge remained practically the same despite extent of detention period. Digested sludge produced in the 3.3-day detention period had only a mild ammonia odor, was very colloidal in nature, and practically impossible to dewater.

Loading studies. Two loading rates were studied in the fifth series of experiments: digester A received 0.09 lb of volatile matter per cu ft of culture volume per day, and B received 0.18 lb volatile matter per cu ft per day. Cultures used in series 4 were placed immediately on the new schedule and adjusted to a 22-day detention period.

Gas production from digester A continued unabated. Digester B showed immediate recovery from the short detention period to which it had been subjected in the previous series, and within 3 days the volume of gas produced daily was almost twice that from A, as would be expected because of the increased loading. Gas produced per lb of volatile matter introduced, however, was almost identical at both loading programs, averaging 8.4 cu ft for digester A, and 8.0 cu ft for B [figure 4 (2)]. Physical characteristics of both sludges were almost the same with respect to dark green color, ammonia, odors, and poor dewaterability.

DISCUSSION

The anaerobic digestion of algae apparently proceeds slowly at mesophilic temperatures and the resultant breakdown is less rapid and complete than that of raw sewage sludge, or a mixture of raw sludge and algae. Accordingly, per cent destruction of volatile matter was only approximately 60 to 70 per cent of that characteristic of raw sludge digestion. The limited extent of destruction was reflected in the low yield of gas per lb of volatile matter introduced. The difference in digester activity was noticeable principally in the extent and rapidity of breakdown, because yield per cu ft of volatile matter destroyed, composition of gas, as well as nature and relative proportions of individual volatile acids were all similar, although the physical characteristics of the digested sludges were quite different. It is probable that in algae digestion, any drastic changes in the nature of the process, as compared to raw sludge fermentation, would have been reflected by equally pronounced changes in the products of digestion, either qualitatively or quantitatively, or both, at least after the initial breakdown of the introduced feed.

It is unlikely that the poor performance of the digesters containing algae and operating at 35 C was due to a high concentration of volatile acid. More probably, the high acid content was a symptom of a low rate of activity rather than a cause of poor digester performance. Experience in previous studies on digestion, in which digesters were given doses of low carbon volatile fatty acids in such volumes as to result in a total volatile acids concentration as high as 4500 ppm, showed that such treatment brings about an increase in gas production proportionate to the acid dosage when other conditions are maintained at an optimum. Volatile acids normally produced in an active digester are not toxic *per se;* instead, they serve as nutrients for many of the bacteria involved in the process. With the exception of formic acid, which may be toxic, any inhibiting effect of a high concentration of low-carbon volatile acids would be indirect, that is, a lowering of pH to undesirable levels. The high pH found in the digesters studied, however, eliminates the latter possibility.

A possible explanation of the limited bacterial activity in the algal digesters is the high ammonia content of the culture media. Ammonia could be detrimental, either as a direct inhibiting agent for the bacteria involved (Snell, 1943), or because it brings about an increase in the pH of the sludge to a level above that tolerated by methane producers. Although digester performance improved in the later experiments, which were also characterized by a high ammonia concentration, gas production and per cent volatile matter destruction in all the experiments involving algae as the source of nutrients remained consistently lower than that encountered when raw sludge was used as a nutrient source. It should be noted, however, that pH levels were always less than 8, the upper limit tolerated by methane producers (Barker, 1949).

The relatively low rate of volatile matter destruction at 35 C also may be explained by the ability of algae to survive in the digester despite the adverse conditions encountered. Living algae normally are immune to bacterial invasion and are not, therefore, subject to decomposition. As such, they are unavailable as a nutrient source to the bacteria involved in the digestion process. Although their viability could not be demonstrated by subculturing, examination of the sludge did reveal intact, green cells apparently in good condition. These cells could have been living organisms which have survived since the previous day's feeding; as such they would illustrate the ruggedness of the organisms and their resistance to destruction.

Another possibility is that algal cell walls *per se* may be highly resistant to bacterial attack, even though the cell itself is no longer living, and thus decomposition of algal cells may be curtailed. Results of studies on the digestion of garbage and sludge mixtures and of vegetables alone have been reported (Babbit, 1934; Carpenter *et al.*, 1936; Cohn, 1946; Hazeltine, 1951; and Ross, 1954). In general, no difficulty was encountered in digesting these materials. Total gas production, as well as rate and per cent decomposition, were comparable to those characteristic of raw sludge digestion. Plant fragments present in garbage, however, are the ground portions of larger plants, and therefore are open to bacterial invasion; algae, on the other hand, although minute and single-celled, are complete organisms introduced onto the digester intact, and consequently are highly resistant to bacterial attack.

Digested sludge from the raw sewage sludge digesters and from the algae digesters differed markedly. The raw sludge product had the tarry odor and gritty nature of well-digested sludge. It dewatered readily. Digested algae, on the other hand, regardless of operating conditions, always had the odor of cow manure encountered in green pastures. The sludge itself contained very little granular or flocculant material and was highly colloidal in nature. Because of its hydrophilic nature, it dewatered slowly. These physical characteristics probably may be explained by the nature of the raw material used as a nutrient source. The highly proteinaceous composition of the algal cell, together with its lack of a complex cellulosic structure, all tend to give rise to a highly colloidal sludge rather than a flocculant or fibrous material easily separated from water. The high nitrogen content of the algal feed also contributed to the formation of a digested sludge having a low carbon: nitrogen ratio, namely, 1:5.

It is interesting to note that algae were digested somewhat more readily at thermophilic temperatures (50 to 55 C), as was shown by the consistently greater gas production per lb of volatile matter introduced and extent of destruction of volatile matter. This is not necessarily the case for raw sludge digestion. Probably, algae die rapidly at these temperatures, or perhaps the heat makes the cell walls more pervious to bacterial attack. It is problematic whether or not the improvement can be explained solely by the beneficial effect of increased temperature on the digestion process itself. Previous experience and the work of others (Heukelekian, 1933; Garber, 1954) have shown no great difference in efficiency of digestion of raw sludge at either mesophilic or thermophilic temperatures within the range 35 to 60 C inclusive. Despite the improvement at 50 C, cu ft of gas produced per lb of volatile matter introduced never equalled that obtained with raw sewage sludge.

Alum, apparently, is a mere dilutant and has neither a detrimental nor a beneficial effect on the microorganisms functioning in the digestion process. This fact is especially important because the greater part of algae used in digester installations will be obtained through alum flocculation until some other satisfactory method of harvesting is developed. The use of alum flocculated feed also had no effect on the physical quality of the digester sludge.

For digesting algae, short detention periods involving highly dilute feed are desirable because of the expense of dewatering algal concentrates to the degree required for economic drying. Our experiments show that algae can be digested successfully at detention periods as brief as 11 days, using feed having a total solids content as low as 1.92 per cent. At detention periods of less than 11 days, the volume of culture removed each day probably depletes the total bacterial population to such an extent that an insufficient number of organisms are available for breaking down the incoming organic material. Moreover, in very short detention periods the addition of a large volume of new material each day may cause a sudden change in environment, sufficiently great to temporarily inhibit bacterial activities. The results of experiments described in this paper, as well as the experience of others who have made studies on raw sludge digestion, indicate that detention periods can be made much shorter than the traditional 20- to 30-day period without adversely affecting the digestion process (Schlenze, 1944, 1951; Fullen, 1953; Morgan, 1954). It may be possible to digest algae at detention periods as short as a day or two through the use of a digester especially designed for continual feeding and mixing. Such a procedure would eliminate the shock to the digestive process which inevitably results when large volumes of nutrients are introduced into the digesters, and equally large amounts of sludge are withdrawn, as happens when feeding is done only once or twice a day.

As is indicated by the identical performance of the digesters at loadings of 0.09 and 0.18 lb per cu ft per day, in digesting algae, loadings in excess of 0.18 lb per cu ft per day may be used. Judging from the results obtained in the algal digestion studies, it is very likely that such loadings can be successfully duplicated on a large scale operation. In fact, digesters utilizing algae as the nutrient source withstand shock loads greatly in excess of those which would completely stop all activity in digesters utilizing raw sludge. Because of the increased organic yield per unit volume of raw sewage when algae is grown on sewage, and because of the lower rate of destruction of volatile matter, the ability to digest large doses of raw material is important if required digester capacity is to be kept at a reasonable volume in algae digestion. Inasmuch as the average loading rate for digesters using raw sewage sludge varies from 0.05 to 0.11 lb per cu ft per day, and as algae can be readily digested at loadings of 0.18 lb per cu ft per day, adoption of photosynthetic oxygenation with algae removal for secondary treatment of sewage would not require digester capacity greater than that already available in most primary treatment plants.

In general, it may be said that these experiments furnish evidence for believing that algae can be readily digested, albeit with a somewhat lower gas production per lb of introduced volatile matter than is possible when raw sludge or a mixture of raw sludge and algae are used as substrates.

Rate of decomposition, loading capacity, detention period, and high loading tolerance all contribute to make possible the use of present digester equipment without major alterations.

Summary

A comparison was made of the value of raw sewage sludge and of green algae as sources of nutrient in anaerobic digestion. Additional studies involved a determination of the effect of temperature, alum in the algal feed, detention period, and loading on digester performance.

Although per cent destruction of volatile matter and gas production per lb of volatile matter introduced was somewhat less than with raw sewage sludge, green algae grown on domestic sewage and separated either by centrifugation or by coagulation with filter alum digest readily when placed under the proper environmental and operating conditions. Best digester performance is obtained at 50 C with a detention period of 11 to 30 days. The maximum permissible loading rate was not determined, but it is greater than 0.18 lb of volatile matter per cu ft of culture volume per day. Under normal conditions, each pound of algal volatile matter introduced into a digester will yield approximately 8 cu ft of gas, of which approximately 2.5 cu ft will be CO_2; 5.0 cu ft, methane; 0.5 cu ft, hydrogen, nitrogen, and other gases.

In general, digestion of algae is characterized by a tolerance of sudden and wide variations in the environmental conditions under which the process is operating.

References

Babbit, H. E. 1934 Disposal of garbage with sewage sludge. Sewage Works J., **6**, 1103–1108.

Barker, H. A. 1949 Le métabolisme des gaz par les bactéries anaerobies. Ann. inst. Pasteur, **77**, 361.

Caldwell, D. H. 1946 Sewage oxidation ponds—performance, operation, and design. Sewage Works J., **18**, 3, 433.

Carpenter, L., Rogel, A. C., and Grabois, B. 1936 The disposal of garbage in the sewerage system. Sewage Works J., **8**, 728–741.

Cohn, M. M. 1946 Effect of food wastes on sewers and sewage treatment. Sewage Works J., **18**, 477–483.

Fink, H., Schlie, I., and Herold, E. 1954 Über die Eiweissqualität einzelliger Grünalgen und ihre Beziehung zur alimentären lebernekrose der Ratte. Natürwissenschaften, **41**, 169–171.

Fullen, W. J. 1953 Anaerobic digestion of packing plant wastes. Sewage and Ind. Wastes, **25**, 576–585.

Garber, W. P. 1954 Plant scale studies of thermophilic digestion at Los Angeles. Sewage and Ind. Wastes, **26**, 1202–1216.

Gotaas, H. B. and Oswald, W. J. 1954 Photosynthetic reclamation of organic wastes. Sci. Monthly, **79**, 6, 368–378.

Hazeltine, T. R. 1951 Addition of garbage to sewage. Water & Sewage Works, **86**, 4 R 151.

Heukelekian, H. 1933 Digestion of solids between the thermophilic and nonthermophilic range. Sewage Works J., **5**, 757–762.

Kellen, W. R. 1956 An ecological study of insects in oxidation ponds. Thesis submitted in partial fulfillment for a Ph.D. degree, Department of Entomology, University of California, Berkeley.

Morgan, P. F. 1954 Studies of accelerated digestion of sewage sludge. Sewage and Ind. Wastes, **26**, 462–478.

Oswald, W. J. and Gotaas, H. B. 1955 Photosynthesis in sewage treatment. Proc. Am. Soc. Civil Engrs., **81** separate no. 686, 1–34.

Ross, W. E. 1954 Dual disposal of garbage and sewage at Richmond, Indiana. Sewage and Ind. Wastes, **26**, 140–148.

Schlenze, H. E. 1944 Controlled garbage digestion. J. Western Soc. Engrs., **49**, 3.273.

Schlenze, H. E. 1951 What you should know about sludge digestion. Public Works, **82**, 10, 67.

Snell, J. R. 1943 Anaerobic digestion. III. Anaerobic digestion of undiluted human excreta. Sewage Works J., **15**, 679–701.

Van Huvelin, W. and Svore, J. H. 1954 Sewage lagoons in North Dakota. Sewage and Ind. Wastes, **26**, 771–776.