DAIRY WASTES: *Disposal by* Balanced Biochemical Bio-Oxidation

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Questions of dairy waste disposal grow more complex as the dairy industry becomes more concentrated. In the United States a simplified treatment system for small dairies (2,000 to 40,000 gal. of waste) has been developed and is fully described here. Details of a 25,000 gal. waste treatment unit are given.

DAIRIES and milk processing plants produce relatively concentrated wastes when compared with municipal wastes. Disposal poses problems of vital importance to all branches of the industry. Dairy wastes are composites of drainage and washings plus milk solids lost through leaks, spills and the occasional addition of discarded items as well as sanitary sewage emanating from the processing plants. The final organic solids concentration in the waste depends upon the quantity of water used in the plant and upon processing losses. The equivalent percentage loss, based on the weight of milk received daily, may vary from 1% for milk receiving stations to as much as 3% for small market milk dairies[1] and often reaches higher values.[2] Thus a determination of the solids in the wastes gives an indication of the efficiency of the processing plant. A guide has been published showing the approximate quantities of material lost in each type of the dairy processes[3].

Legislation to counter pollution of streams, dissatisfaction with existing equipment and inability of such equipment to treat concentrated wastes from a dairy, led the United States Department of Agriculture to the development of a simplified treatment system for small dairies. Information obtained, procedures developed, principles involved, and the simplified disposal unit evolved may be applicable to treatment of other agricultural processing wastes, as well as wastes from other industries. Details have appeared in many American reviews and discussions[4, 5, 6, 7, 8, 9], but your editor requested a summary of our work for DAIRY ENGINEERING.

Indeed, the magnitude of the problem has been increased through the centralisation of the industry with its strict sanitary codes, as well as the legal and vocative demands for clean streams. Justification of these demands may be understandable from the following : Assume a dairy plant, handling 100,000 lb. of milk per day, loses only 1% of the milk received. The liquid waste will therefore contain the equivalent of 1,000 lb. of skim milk or about 100 lb. of skim milk solids. Complete or ultimate oxidation of the organic matter of these solids will require about 100 lb. of oxygen. Since the solubility of oxygen is only 8.4 part per million (ppm) in fresh water at 25° C[10], all the oxygen in almost 1.2 million Imperial gal. or the amount in a pond 6 ft. deep, 100 ft. wide and 265 ft. long is needed. Once the limited oxygen supply is removed from solution by the micro-organisms living on the waste, none is left for fish or plant life ; disagreeable odours and anaerobic conditions are produced unless the oxygen is replenished by re-aeration.

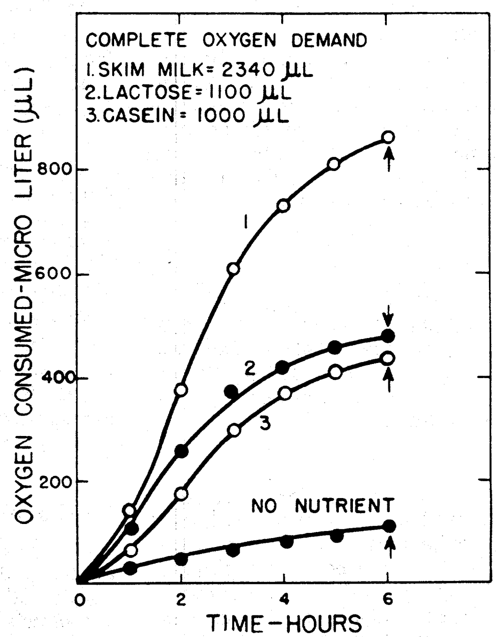


Fig. 1. Respirometer study showing high rate of immediate oxygen demand and low rate of demand after assimilation.

* Eastern Utilisation Research and Development Division, Agricultural Research Service, U.S. Dept. of Agriculture.

Laboratory Aerator Investigations

Difficulties in treatment were not encountered when 1,000 ppm of synthetic waste, composed of dried skim milk solution, were vigorously aerated and agitated in a laboratory fermenter maintained at 30° C. Conversion of the soluble wastes was so rapid that the 5-day B.O.D. test was of no value for following the changes. A rapid chemical oxygen demand (C.O.D.) determination used in our studies [11,12] gave values approximating the 20-day or ultimate B.O.D. We understand that this rapid method is finding application as a control test by industry and by some engineers. Factors were established after running the 5-day B.O.D. for various items : 67% of the C.O.D. of skim milk was equal to its 5-day B.O.D.; lactose, 83%; whey, 86%; casein, 54%; and aerated sludge, 49%[13].

Waste fed continuously at the rate of one volume change per day showed, upon testing the input and output, that about one-half of the skim milk was destroyed while the remainder was converted to sludge.[14]. It appeared as if the protein was retained while the carbohydrate was oxidised. Very little material remained in solution. This change may be expressed :

$$\text{Milk solids} + \text{bacterial sludge} + \text{air} \rightarrow \text{more bacterial sludge} + CO_2 + H_2O \quad (1)$$

Results were comparable to those obtained earlier by following the oxidation of lactose by activated sludge.[15] However, information was not yet available as to the readiness in which each ingredient of the waste is oxidised nor as to the amount of oxygen required.

Manometric Studies

Oxidation of skim milk, casein and lactose by a sludge was followed by manometric studies,[16] since other workers have established that carbon dioxide is the only gas produced in oxidations by sludge[17, 18, 19]. Fig. 1 shows the rate and amount of oxidation of unfed sludge and of skim milk and its two principal components in the approximate proportion that they occur in skim milk. These manometric experiments showed that the high rate of oxygen demand dropped in about 6 hr., when 2 parts of milk solids were treated with one part sludge. Casein and lactose were oxidised easily and at about the same rate, showing that both were readily available to the organisms. The unfed sludge having no added nutrients also required oxygen, although at a slower rate. Satisfaction of the complete oxygen demand was not required for stabilisation. The assimilation step used only an average of about 37.5 to 40% of the calculated amount of oxygen needed for complete combustion. The remaining 60 to 62.5% of oxygen-demanding substrate was assimilated.

Empirical Formula for Sludge

Detailed consideration of the above information required a chemical analysis of well aerated cells. An empirical formula, $C_5H_7NO_2$, with a " mole " weight of 113, was obtained omitting phosphorus and sulphur.[20] This formula was used to determine the equations of syntheses for the conversion of lactose, casein and skim milk to sludge.

Cell Formation from Lactose

Sugar is completely oxidised to carbon dioxide and water to yield energy, thus,

$$C_{12}H_{22}O_{11} + H_2O + 12O_2 \rightarrow 12CO_2 + H_2O \quad (2)$$

or expressed for convenience as the monomeric unit :

$$(CH_2O) + O_2 \rightarrow CO_2 + H_2O \quad (3)$$

The empirical sludge cell, $C_5H_7NO_2$, requires the addition of ammonia for its formation from lactose. If the ammonia and sugar are incorporated into cells, the following equation is obtained :

$$5(CH_2O) + NH_3 \rightarrow C_5H_7NO_2 + 3H_2O \quad (4)$$

The above equation (4) neglects the actual amount of oxygen consumed, which according to the manometric data was 37.5% of the total oxygen requirement. Thus, 3 out of 8 carbons (37.5%) were completely oxidised while 5 carbons were assimilated :

$$8(CH_2O) + 3O_2 + NH_3 \rightarrow C_5H_7NO_2 + 3CO_2 + 6H_2O \quad (5$$

According to equation (5), the expected cell yield should be 47% of the lactose. When the 8.6% ash content of the sludge cells is considered, yields of 52% should be expected.

Cell Formation from Casein

An analysis of the casein, disregarding phosphorus and sulphur, gave the formula $C_8H_{12}NO_3$, which had a " mole " weight of 184. Casein is completely oxidised thus :

$$C_8H_{12}N_2O_3 + 8O_2 \rightarrow 8CO_2 + 2NH_3 + 3H_2O \quad (6)$$

Again, to satisfy the manometric data the minimum equation for assimilation of casein into cell substance may be written :

$$C_8H_{12}N_2O_3 + 3O_2 \rightarrow C_5H_7NO_2 + 3CO_2 + NH_3 + H_2O \quad (7)$$

According to equation (7), a greater sludge yield would be expected from protein than from sugars, 61% on ash-free basis or 68% including ash.

Cell Formation from Skim Milk

An examination of the above equations shows that either 240 units of sugar or 184 units of casein produce 113 units of ash-free cells. Fortunately, these are essentially the proportions of lactose and casein found in milk. Hence, the two assimilation equations were added together to give :

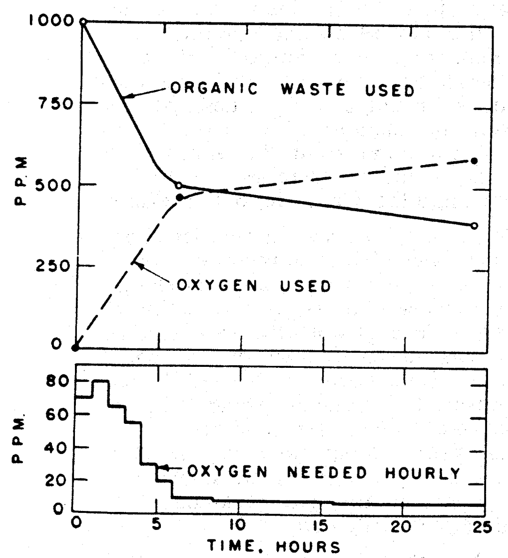


Fig. 2. Graphical compilation of laboratory experiments when 1,000 ppm milk were added in one dose to 500 ppm sludge solution. Note sharp break in oxygen demand after assimilation.

$$8(CH_2O) + C_8H_{12}N_2O_3 + 6O_2 \rightarrow 2C_5H_7NO_2 + 6CO_2 + 7H_2O \qquad (8)$$

The ammonia liberated in the oxidation of casein satisfies the nitrogen required for lactose assimilation. Actually, in the aeration of skim milk wastes, the mixed liquor remains at about *p*H 6.7. Sludge yields were slightly less than the 53% shown in equation (8) or 58% including cell ash. The difference may be due to endogenous respiration or aerobic digestion of the sludge as well as other factors.

Endogenous Respiration

The above equations express the synthetic or assimilative reactions. Cells also have a reaction called endogenous respiration in which they oxidise their own cells for energy :

$$C_5H_7NO_2 + 5O_2 \rightarrow 5CO_2 + NH_3 + 2H_2O \qquad (9)$$

The rate of oxygen required for aerobic autodigestion is considerably less than that required for assimilation[21]. A 10-fold difference existed between the assimilation and endogenous phases. According to equation (9), a unit of cell consumes 1.43 weight units of oxygen for complete oxidation. At 30° C., it was shown that 0.5 to 1% of the cells was oxidised per hr.[22] At 1% per hr., the sludge burn-up would be 20% per day during the first day. Endogenous respiration stabilised-sludges from various wastes have shown reductions in sludge weights varying from about 5%[23] to 23%[24] for the first day.

Oxygen Utilisation

Polarographic measurements of oxygen depletion were made on 500 ppm sludge with varying amounts of skim milk[20]. The time necessary for oxidation of the waste was directly proportional to the concentration of the waste above a concentration of 100 ppm. Therefore, if 1,000 ppm waste were assimilated in 6 hr., 500 ppm would be assimilated in about 3 hr., and so on. Later tests showed that waste oxidation and purification were related to the amount of available sludge.[25] Increasing the sludge concentration increased the rate of waste removal and hence increased the rate of oxygen utilisation by the mixed liquor for a shorter period of time. The rate of oxygen required dropped to that of endogenous respiration when assimilation was completed.

Purification of Dairy Waste

The removal of milk solubles from solution under aerobic conditions appears to be simple oxidation and assimilation. However, the processes are more involved, as shown by the rates of purification or clarification, which were 10 times greater than the rate of oxidation when 1,000 ppm each of sludge and skim milk were vigorously aerated.[25] Further study showed that a well-aerated endogenous sludge was able to convert lactose to a glycogen-like product.[26] As much as one-third of the sludge weight may be storage carbohydrate. This storage material is readily available to the cell, disappears rapidly and is practically gone when the assimilation step is completed. This property of storage and oxidation of stored material has been used in the purification of cannery wastes.[27] Incoming waste is aerated for about 30 min. with a high concentration of sludge cells. The sludge is removed and aeration continued in a separate tank; the endogenous sludge is re-used. Schematically, clarification and purification may be as follows :

Soluble Wastes
↓
Purification
↓
Removal of Solubles (→ Storage; → Oxidation)
Storage → Oxidation
Storage → Cell Synthesis (Assimilation)
Removal of Solubles → Cell Synthesis (Assimilation)
Oxidation → $CO_2 + H_2O$
Cell Synthesis (Assimilation)
↓
Endogenous Respiration
↓
$CO_2 + H_2O + NH_3$

Data on One Dose Feeding

A graphical summary of the laboratory results is shown in Fig. 2 in the case when 500 ppm of sludge solids and 1,000 ppm of milk solids are aerated. Added organic matter decreases about 50% during the first 6 hr. with a concurrent rapid use of oxygen. This is followed by a sharp decline in organic matter oxidation during endogenous respiration with much lowered oxygen requirements. The stabilised sludge is oxidised very slowly. The micro-organisms involved in these processes do not remain stable but are in continual change.[28]

The following tabulations were made on the basis of a one dose feeding of 1 lb. of ash-free skim milk solids dissolved in 1,000 lb. of water (1,000 ppm).

Oxygen required for complete oxidation of 1 lb. skim milk organic matter ..	1.20 lb.
Oxygen used for assimilation only (37.5%)	0.45 lb.
Time required for assimilation	
With 500 ppm cells	6 hr.
With 1,000 ppm cells..	3 hr.
Oxygen required per hr. depends on cell concentration	
With 500 ppm cells	0.075 lb.
With 1,000 ppm cells	0.150 lb.
New sludge cells produced	0.53 lb.
Oxygen for complete burn-up of new cells	0.75 lb.
Oxygen needed for endogenous respiration during first 24 hr. varies.	
If 1% per hr., then 20% per day ..	0.15 lb.
If 0.5% per hr., then 10% per day ..	0.075 lb.
Seed sludge cells have respiration requirements.	
Oxygen to oxidise 1 lb. sludge organic matter	1.42 lb.
Oxygen to oxidise 20% or 0.2 lb. per day	0.29 lb.
Oxygen to oxidise 10% or 0.1 lb. per day	0.15 lb.

Pilot Plant Studies

The applicability of the laboratory data to pilot plant was investigated at the Pennsylvania State University, where the college creamery had a supply of 10,000 gal. of waste daily.[29] Initial trials gave the same incomplete treatment as observed at many other dairies. Oxygen available in solution was insufficient to satisfy the demands as shown by the equations and in the tabulation. Various types of customary aeration equipment tested were unable to satisfy the high oxygen demand of dairy wastes.

Oxygen transfer efficiency tests of the aerators used pointed to the cause of the difficulty[30]. For example, as little as 1% of the oxygen in air forced through a sparger made of perforated pipe was dissolved in water, while 2 to 5% solution was obtained with porous plates. Impingement types of aeration equipment gave up to 10% oxygen transfer efficiency. A specific type large size jet aerator or aspirator showed that 17 to 25% of oxygen was transferred. Turbine-type equipment may give high efficiencies also.

Jets or aspirators (2.5 in. pipe size) were then installed in the pilot plant, and operation continued a number of years without difficulty. Each jet of the specific type supplied 1.6 lb. of oxygen per hr. under operating conditions described for the industrial installation. This oxygen was obtained by aspiration from the atmosphere. Oxygen supply could be increased by 40% if air was forced into the inlet under 6 lb. pressure.

A simple fill-and-draw system was developed that gave high rates of B.O.D. removal with no apparent or only slight accumulation of sludge. Aeration was sufficient to assure satisfaction of the high oxygen demand when the waste entered the tank. Occasional shock loads of whey could be handled.[29] The sludge readily settled, permitting removal of the clear supernatant liquid. The residual aerated sludge served as seed for the following day's run. Odour was absent, removal of solubles was rapid, and excess sludge was digested by proper aeration over week-ends. The process can be practically automatic.

These pilot plant trials definitely showed that laboratory results can be used to design a waste treatment plant. It is necessary to know the amount of waste and its oxygen demand. Above all, equipment and conditions must be selected or designed to satisfy the oxygen requirements at the time the oxygen is needed.

An Industrial Installation

We have been told that over 60 dairies use treatment units based on the above principles. Some handle as little as 2,000 gal. of waste daily by the fill-and-draw method, while the largest is a continuous treatment plant with facilities for sludge settling and sludge return that treats about 150,000 gal. of waste daily.

Even before the pilot plant investigations were completed, the fill-and-draw system was installed at a commercial dairy as it offered the least costly and an assured means of treatment.[31] The system has now been in operation for more than three years; the effluents meet the requirements of the pollution control agencies. Over 95% purification is reported. Details of this plant may be of interest in order to show the calculation for such treatment units.

The size of a plant is determined by the volume of the settled sludge cells and volume of waste to be treated. Pilot plant operation showed that 1 lb. of cells occupied 0.8 cu. ft. when settled for 30 min. Total weight of cells may be estimated from the milk solids in the waste, since half their weight is convertible to new cells. Pilot plant data showed that sludge oxidised itself endogenously at 1% per hr. or 20% per day. Thus, when conditions of equilibrium are attained, the weight of cells in the aerator equals 2.5 times the

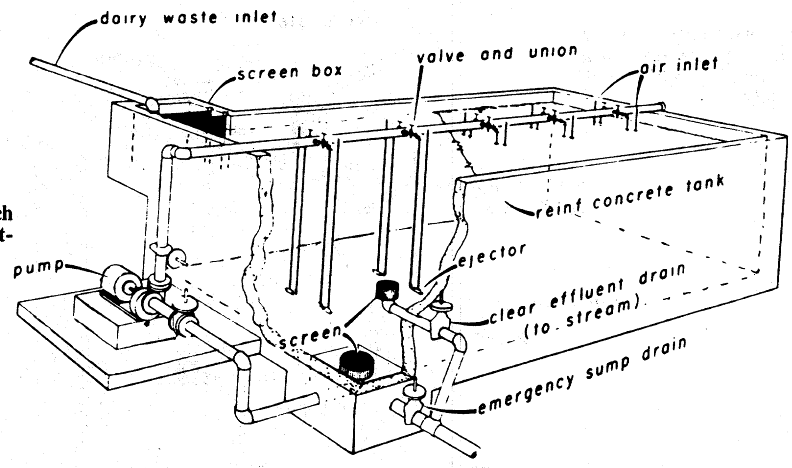


Fig. 3. Typical batch type dairy waste treatment plants.

weight of milk solids received in the waste. Under such ideal conditions, accumulation of sludge is at a minimum, since the amount of new sludge produced per day should equal the amount of sludge oxidised.

The following calculations were made on a daily basis using information from the previous tabulation and analytical data.

Milk received	100,000 lb.
Losses, assume 2.5%	2,500 lb.
Waste volume	25,000 gal.
Milk solids loss	300 lb.
Plant operation, per day	8 hr.
Loss per hr.	37.5 lb.
Oxygen required per hr. for assimilation	16.9 lb.
Cells produced per day	150 lb.
Cell solids in aerator	750 lb.
Settled sludge volume	600 cu. ft.
Sludge burn-up per day	150 lb.
Oxygen required by sludge	213 lb.
Oxygen required per hr. by sludge	9.7 lb.
Oxygen requirements per hr. for assimilation and endogenous respiration	26.6 lb.
Oxygen required after settling and draining	9.7 lb.
Freeboard above settled sludge	600 cu. ft.
Waste volume	3,330 cu. ft.
Minimum tank size	4,530 cu. ft.
Minimum tank capacity	34,000 gal.
Effluent pipe at level of	9,000 gal.

The estimated strength of this waste would be about 1,450 ppm C.O.D. or about 1,000 ppm B.O.D. Actual analyses of one day's run gave a higher value of 1,650 ppm for the 5-day B.O.D.

The same size jet aerators* used so successfully in the pilot plant were installed. Recirculating the waste through the jet at 60 gal. per min. dissolved the 1.6 lb. of oxygen required per hr. Thus, 17 jets should supply the theoretical maximum oxygen demand of 26.6 lb. per hr. However, 24 jets are in operation to allow for excessive overloading and plant expansion. Two centrifugal pumps operate the 24 jets during the day, then at night one pump recirculates the wastes through all the jets. Although this plant is designed to treat between 300 to 400 lb. of solids, it has handled up to 700 lb. at times without difficulty.

The operation of the plant is simple. The required sludge may be developed by adding sludge from any activated sludge process, by inoculating with a soil extract or by continual aeration of the waste itself. Desirable aerobic micro-organisms become established.

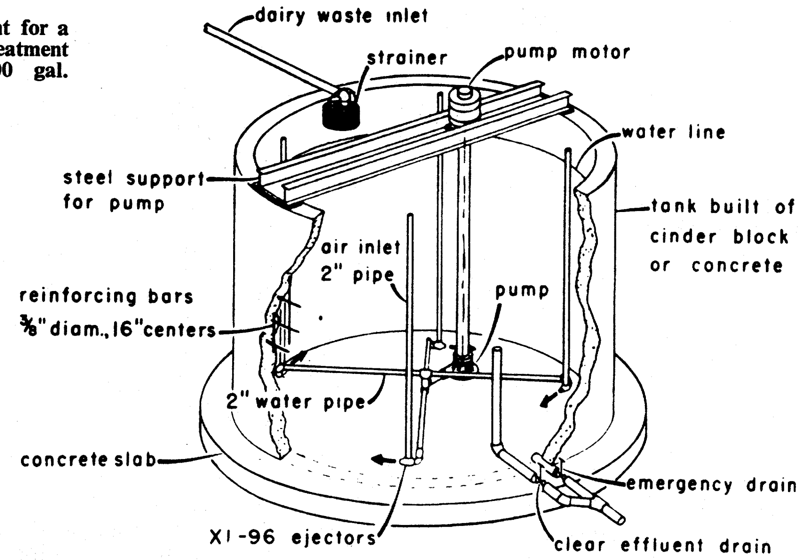
When the dairy begins operation in the mornings and waste begins to flow to the aeration tank, the 24 jets are put in operation at maximum air flow. This continues as long as waste is received during 8 hr. and continues for another hour. Power is then shut off and the sludge settles for about 2 hr. Then the effluent pipe is opened to drain the clear liquid. This liquid enters a small pond in which fish and aerobic forms of life abound. The overflow from the pond enters a small brook and tests show about 5 ppm B.O.D.

When the supernatant liquor is drained from the tank, the valve is closed. Aeration of the remaining sludge is continued throughout the night at a low rate by use of one pump. Next morning, full aeration is applied again, as fresh waste enters the tank.

Although it is claimed that sludge accumulation does not occur, it is probable that cell increase does take place as ideal conditions do not exist in such an aeration unit. For example, during cold weather or periods of excessive loading, sludge should accumulate, since endogenous respiration would be slow in the former

* The specific jets used are manufactured by the Penberthy Injector Company of Detroit, Michigan. The ejector found most satisfactory in this study was the XL96 type, size 7A (Steam nozzle). It is not implied that the U.S.D.A. recommends the above company or its product to the possible exclusion of others in the same business

Fig. 4. Arrangement for a small dairy waste treatment plant handling 5,000 gal. waste daily.



case[26] and would not burn up all the excess in the latter. This treatment unit has no sludge disposal facilities, and it is possible that a small amount of sludge is present in the clear effluent and is used by the animal and plant life in the pond. At a future date, arrangements to get rid of accumulated sludge can be made. At present, none is needed.

Schematic Diagrams

Fig. 3 shows a fill-and-draw waste treatment installed with 10 ejectors. Such a set-up will supply 16 lb. of oxygen per hr. Air is aspirated through the pipes projecting above the surface of the tank. The screen is installed to prevent the clogging of jets by closures and other large debris. Many installations have the jets spaced along the outer walls of the aerator or along a dividing wall between two portions of the tank.

A simple design showing all necessary features is shown in Fig. 4. Such a plant is treating 5,000 gal. of waste from a small bottling plant surrounded by many homes. When properly operated, no difficulty arises in the neighbourhood.

Fig. 5 gives a schematic diagram of a continuous process dairy waste treatment plant. In this case additional air is supplied by an air pump to satisfy the oxygen demand of the concentrated waste in a short time. The settled solids from the settling tank are pumped back continuously through the ejectors. Another installation pumps the sludge solids directly into the aeration tank and recycling is done with the mixture from the aeration tank. The rate of sludge settling must be determined in such a system in order to allow sufficient space to assure clear effluents.

The above discussion presents the use of jet aerators or aspirators only. Other types of aeration devices may be satisfactory, but careful study must be made to assure correct amounts of dispersed oxygen. Such aeration devices vary from the suggested new style aerator of a simple corrugated lattice made of plastic[31] to an adaptation of the mechanical aeration device used for yeast production[32].

Application of many of these principles to engineering design is discussed under the title, " Bio-calculations ".[33] The various facets of the bio-oxidation processes are presented, including such factors as aeration, detention period, oxygen demand rates and air requirements, sludge production, nutrient requirements, solid-liquid separation and their use in plant design.

Costs

Industry realises that waste treatment is a necessary item of cost. Supplying sufficient air to maintain aerobic conditions requires power. The selection of the most desirable equipment to do a proper job must be left to the discretion of the engineer. However, the engineer should have an understanding of the bio-oxidation process and realise that he is working with living organisms in order to properly design this type of a treatment plant.

According to the proprietor of the dairy, whose treatment plant was described in the section, " Industrial Installation," the costs were nominal for enlarging the existing tank and installing aeration equipment. With the use of plant labour, expenditures were held to about $7,000. On the other hand, bids of about $40,000 had been received for the installation of a conventional

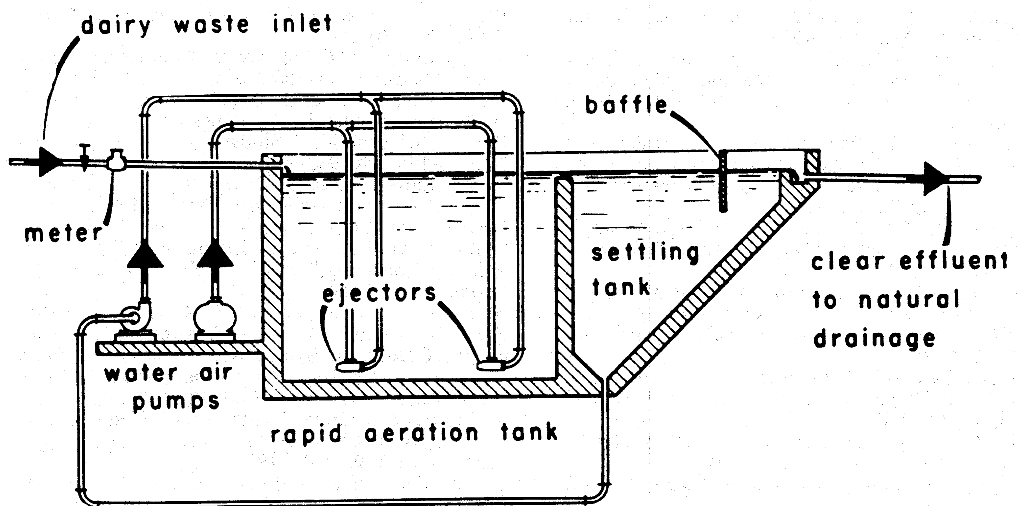


Fig. 5. Schematic diagram of continuous process dairy waste treatment plant with air supplied under pressure.

activated sludge plant without assurance of satisfactory treatment. Another dairy, having about 40,000 gal. of waste daily, installed similar equipment and made changes at a cost of about $12,000. The daily operating cost for power at the latter dairy is about $6. A small unit to treat 2,000 to 5,000 gal. of waste should cost proportionately less. The one tank fill-and-draw system can be easily installed at a nominal cost and is simple to operate.

Acknowledgment

The laboratory investigations were carried on with the active assistance of Miss Lenore Jasewicz, my co-worker, and with the cooperation of Dr. Sam R. Hoover. Pilot plant investigations were under the direction of Professor of Sanitary Engineering, R. R. Kountz at Pennsylvania State University.

Summary

Principles have been developed that assure proper treatment of such concentrated wastes as produced by dairies.

Oxygen requirements during the clarification or purification of a waste are delineated.

High rates of oxygen demanded by the actively living sludge cells during assimilation must be satisfied in order to maintain aerobic and odourless conditions.

Stoichiometric equations and tabulations are given to show the relations between waste solids, oxygen requirements and sludge solids.

Data are presented as weight units of oxygen required, not as volume of air passing through the waste. Hence, correct equipment to dissolve the required oxygen must be selected on this basis.

Simple one tank fill-and-draw systems to treat 2,000 to 40,000 gal. of waste are in operation as a result of laboratory and pilot plant studies. Continuous flow systems have also been installed.

Design and operation of a 25,000 gal. dairy waste treatment unit are described in detail.

Estimated costs, especially for treatment of wastes at small dairies by the rapid aeration method, are considerably less than treatment by conventional methods.

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