STABILIZATION POND DESIGN CRITERIA FOR TROPICAL ASIA

M. G. McGarry & M. B. Pescod
Environmental Engineering Division
Asian Institute of Technology
Bangkok, Thailand

INTRODUCTION

Stabilization ponds have been used for wastewater treatment in many countries of the world and are considered most suitable for tropical developing countries. However, Asian governments are only now paying attention to environmental pollution and taking an active interest in feasible wastewater treatment processes. The particular aspects of stabilization pond treatment which make it most applicable to tropical developing countries are the low cost of construction, advantageous climatic factors, ease of operation, and lack of foreign exchange requirements for purchase of mechanical equipment. A major disadvantage of this form of treatment is the large land area requirements associated with ponds. Land use is most efficient if anaerobic and facultative ponds are operated in series. Best use of land area is achieved through maximization of areal BOD removal in any type of stabilization pond. This paper will use areal BOD removal in lb/acre day of 5 day, 20°C BOD, as the most important basis for comparing pond systems. The performance of both anaerobic and facultative ponds as primary units will be considered and the possibilities of series operation of multi-stage anaerobic ponds will be investigated.

ANAEROBIC PONDS

Anaerobic ponds have been found to tolerate higher loadings than facultative ponds and give high BOD removals. However, they can give rise to odours which have often limited their use to remote areas. In Asia, where there has been little or no treatment of sewage or industrial wastes in the past, the aesthetic sensitivity of the population is not so developed as in western countries. Providing that wastes are handled in the future in an organized way at minimum cost and with minimum land use, it is unlikely that Asian people will object to odours. Economic factors are almost certain to override any other consideration in deciding upon a method of wastewater treatment. If the constraint of odourless treatment is eliminated, anaerobic ponds can be designed as highly efficient reactors for BOD removal. Otherwise, operational measures will have to be incorporated into the design and will almost certainly affect the BOD removal efficiency.

In his review of anaerobic pond systems design, OSWALD (1968) discussed the influence of a number of specific environmental factors on the transformations which occur in anaerobic conditions in a pond result from the level of applied BOD loading and that neither nutrient deficiency nor the presence of toxic substances limit the development of a satisfactory microbial population, the anaerobic pond environmental factors most important in the tropics are detention time and pH. The temperature level will normally be conducive to efficient anaerobic breakdown of organic matter, the higher the temperature the more efficient the system performance.

Areal BOD Loading of Anaerobic Ponds

Removal of BOD in anaerobic ponds is brought about both by sedimentation and anaerobic digestion. BOD loading on ponds is often reported as a surface area loading in lb/acre day, this being consistent with the sedimentation function, but a volumetric loading is more appropriate to anaerobic digestion. The BOD loading rate specified should reflect the predominating function but no systematic study of these variables has been reported. Of course, sedimentation will only effect BOD removal if the influent waste contains settleable organic solids. Ponds usually provide sufficient detention time to allow efficient sedimentation. A pond loaded at a rate of 5000 lb BOD/acre day with a weak sewage of 200 mg/l BOD has a surface overflow rate of 69 gal/ft^2 day, which is low for sedimentation tank design. On this basis it seems unreasonable to adopt sedimentation as the overriding consideration in design loading. Since optimum conditions in anaerobic ponds occur in the absence of oxygen and because algae are not involved in the process, oxygen transfer or light reception at the surface cannot be important. The only justification for using areal BOD loading in connection with anaerobic ponds is if biological conversion of organic material suspended or dissolved in the supernatant overlying deposited sludge is dependent on the area of sludge exposed. PARKER *et al.* (1950) and PARKER and SKERRY (1968) pointed out the importance of the sludge layer in BOD removal yet suggested in the earlier paper that a volumetric BOD loading might be the more appropriate parameter. If an anaerobic pond is considered a biological reactor similar to a digester, then volumetric loading is the most useful parameter. Reports on the use of anaerobic ponds for treatment of industrial wastes high in BOD have usually adopted volumetric loading rates and STEFFEN (1968) was most definite in suggesting that loading of this type of pond was a volume characteristic. Specification of loading rate in volumetric terms would allow a trade-off between land cost and construction cost for deep ponds. In spite of volumetric BOD loading and removal parameters being considered the more appropriate forms, the more conventional areal BOD loading and removal rates will generally be used in this discussion. Practical advantages of these forms are that an immediate indication of land use is given and performance results are more directly comparable with those from facultative ponds. It is hoped, however, that future research will be directed towards establishing which is the more rational loading parameter.

Anaerobic pond performance data from various countries as reported in the literature have been collected and are presented in Figure 1 for BOD loadings up to 6000 lb/acre day. Much higher areal BOD loadings have been used in practice with success. For example, BOD loadings up to 46,400 lb/acre day were reported by STANLEY (1966) to give areal BOD removals as high as 37,100 lb/acre

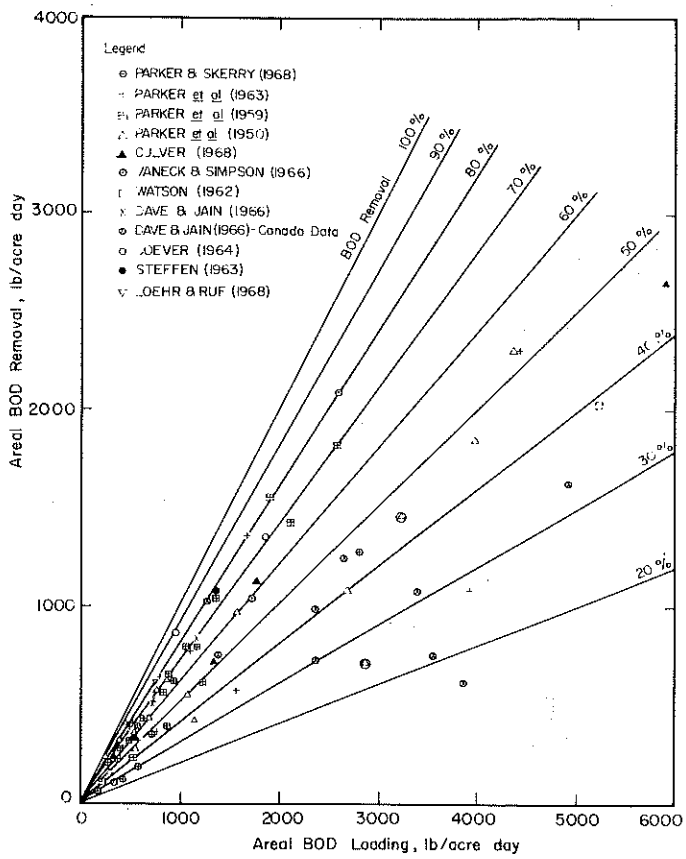


Figure 1. - Reported performance of anaerobic ponds

day in treating packing house waste in deep ponds. The only inference that can be drawn from the plot in Figure 1 is that high BOD loading gives high BOD removal. Further rationalization of these data is not possible because the environmental factors influencing performance are many and their levels have often not been reported. However, many workers have noted a loss of efficiency during winter operation compared with summer, and thus temperature may be considered to have a significant influence on the performance of anaerobic ponds. Because of high ambient temperatures throughout the year, high BOD removals can be expected in ponds in tropical countries, even with high areal BOD loadings. More recent data collected at the Asian Institute of Technology in Bangkok, Thailand, and previously unpublished, are presented in Figure 2 and show the very high areal BOD removals which can be attained with experimental control. Again the trend of high BOD removal at high BOD loading rates is apparent.

The influences of the three factors areal BOD loading, detention time, and influent pH on areal BOD removal were studied by UDDIN (1970) in a factorially designed experiment, each factor at two levels. A plant waste from the production of tapioca starch was fed to 3 ft deep experimental ponds. Table 1 gives the levels of the factors and the BOD removals obtained at steady-state conditions with an average temperature of 77°F. Areal BOD removal was maximum at the highest of the two levels of each of the independent variables. A variance analysis of the data showed the effects of areal BOD loading, influent pH, detention period, and the interaction between loading and influent pH to be significant in the areal removal of BOD (95 percent confidence) in the order given.

Effect of Detention Period on Anaerobic Pond Performance

AMALORPAVAN (1963) suggested that the rate of anaerobic decomposition increases with time, reaches a maximum and then decreases. If this is so, there will be an optimum pond detention period, at any particular BOD loading, above which it will be inefficient to operate. GLOYNA (1965) supported this by stating that detention times longer than five days are not justified because the performance in anaerobic ponds then becomes comparable with that in facultative ponds. He also gave an empirical formulation, as recommended by VINCENT *et al.* (1963), to estimate the degradation action occurring in pretreatment anaerobic ponds in tropical areas, assuming complete mixing and for the pH range 6.8 to 7.2, as follows:

$$P = \frac{P_o}{6\left(\frac{P}{P_o}\right)^{4.8} R + 1} \qquad (1)$$

where, P = Pond and effluent 5-day, 20°C BOD, mg/1
P_o = Influent 5-day, 20°C BOD, mg/1
R = Retention time for completely mixed separate pond system, days

Since this formulation does not include a pond depth term, the predicted performance is not related to areal BOD loading rate but does take account of detention period.

PARKER *et al.* (1950) first presented data demonstrating the influence of detention period on the performance of anaerobic ponds at Werribee, Victoria,

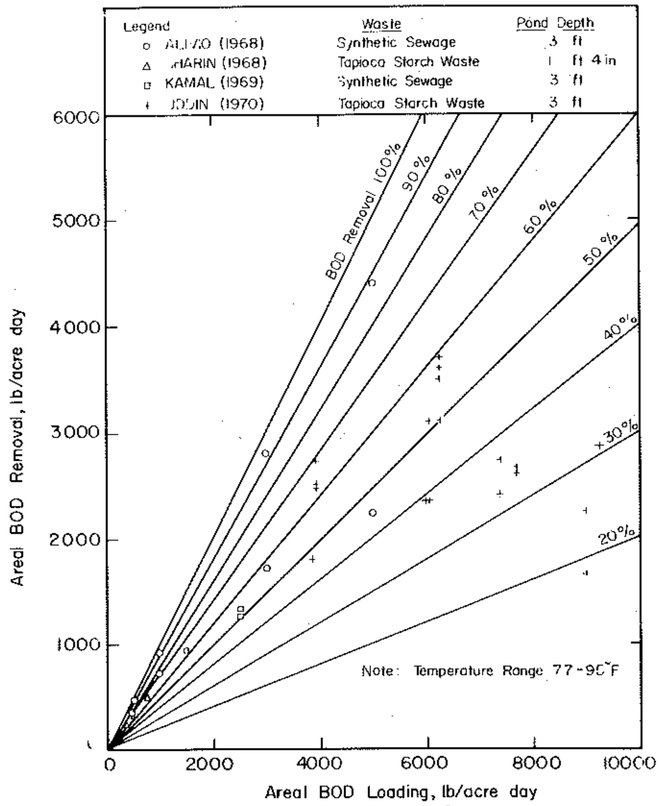


Figure 2. - Performance of experimental anaerobic ponds in Thailand

Table 1 – Effect of Loading, Detention and pH on BOD Removal in Anaerobic Ponds

Pond No.	BOD Loading, lb/acre day	Detention Period, days	Influent pH	Influent BOD, mg/1	Effluent BOD, mg/1	BOD Removal	
						lb/acre day	%
1	2100	1	4	260	150	680	32.5
2			7	260	110	1210	57.6
3		2	4	510	310	830	39.3
4			7	510	140	1520	72.6
5	5830	1	4	710	520	1560	26.8
6			7	710	350	2960	50.8
7		2	4	1430	1000	1760	30.1
8			7	1430	600	3380	58.0

Table 2 – Performance of Anaerobic Ponds (after PARKER & others, 1950)

Unit No.	Det. Time days	Area, acre	Period*	BOD Applied lb/day	BOD Loading lb/acre day	BOD Removal* lb/acre day	BOD Removal lb/day	BOD in Effluent lb/day
1	1	0.0198	1	78.7	3980	1862	36.9	41.8
			2	86.9	4390	2309	45.7	41.2
			3	64.8	3270	1469	29.1	35.7
			4	56.8	2870	702	13.9	42.9
			5	53.0	2680	1093	21.7	31.3
2	1½	0.0297	1	41.8	1410	391	11.6	30.2
			2	41.2	1390	326	9.7	31.5
			3	35.7	1200	196	5.8	29.9
			4	42.9	1440	223	6.6	36.3
			5	31.3	1050	196	5.8	25.5
3	2½	0.0495	1	30.2	610	190	9.4	20.8
			2	31.5	637	137	6.8	24.7
			3	29.9	604	167	8.3	21.6
			4	36.3	733	150	7.4	28.9
			5	25.5	515	177	8.8	16.7
4	5	0.0990	1	20.8	210	60	5.9	14.9
			2	24.7	249	169	16.7	8.0
			3	21.6	218	65	6.4	15.2
			4	28.9	292	55	5.4	23.5
			5	16.7	169	93	9.2	7.5
1+2	2½	0.0495	1	78.7	1590	981	48.5	30.2
			2	86.9	1750	1122	55.4	31.5
			3	64.8	1310	706	34.9	29.9
			4	56.8	1150	415	20.5	36.3
			5	53.0	1070	556	27.5	25.5
1+2+3	5	0.0990	1	78.7	795	583	57.9	20.8
			2	86.9	877	628	62.2	24.7
			3	64.8	655	435	43.2	21.6
			4	56.8	574	282	27.9	28.9
			5	53.0	535	365	36.3	16.7
1+2+3+4	10	0.1980	1	78.7	398	324	63.8	14.9
			2	86.9	439	401	78.9	8.0
			3	64.8	327	252	49.6	15.2
			4	56.8	287	170	33.3	23.5
			5	53.0	268	230	45.5	7.5

* from PARKER Paper

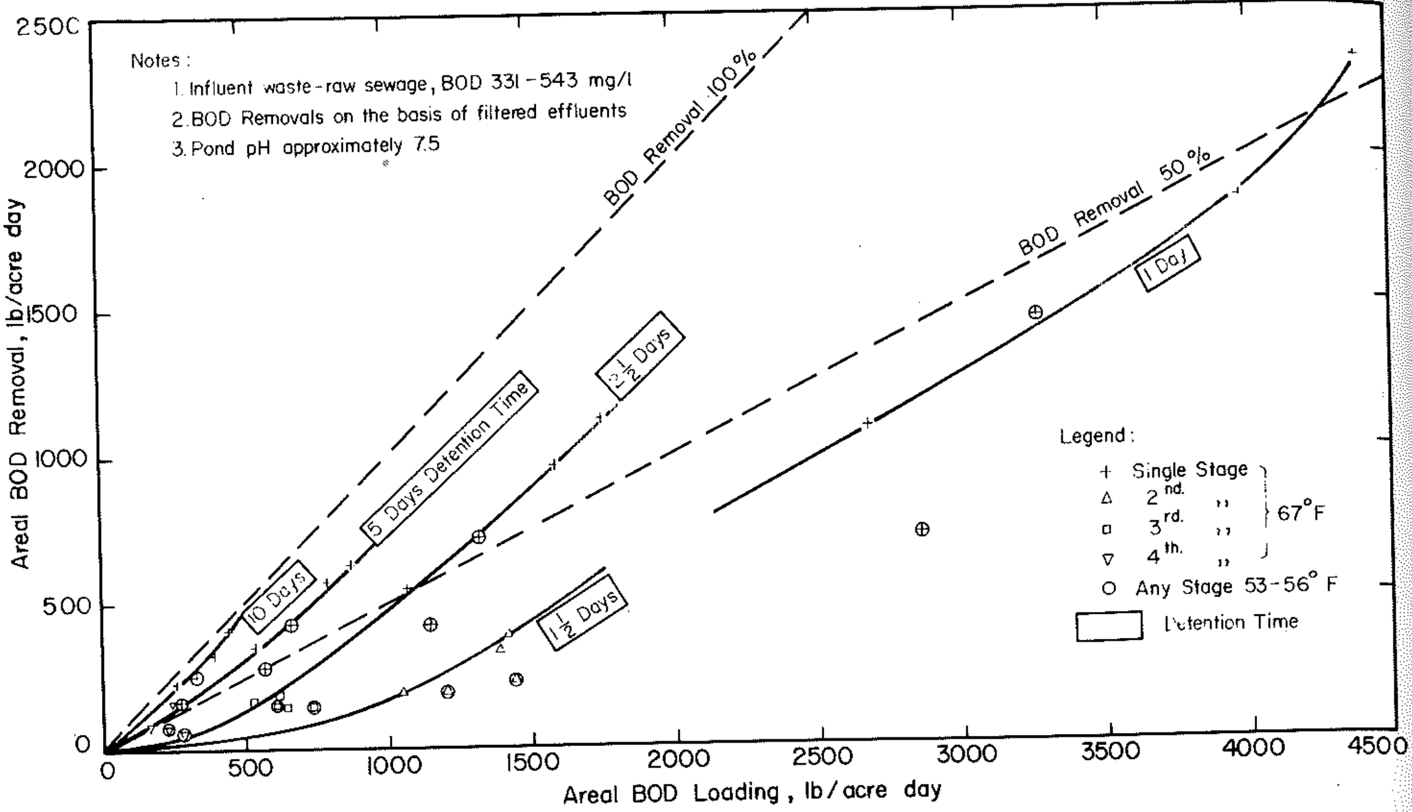


Figure 3. - Effect of detention time on anaerobic pond performance (Data from Parker et al, 1950)

Australia. Table 2 has been prepared, using their data, to show both areal BOD loading and removal at each stage of anaerobic pond unit and average loadings and removals for multiple stages. Figure 3 presents the results from Table 2 in graphical form and clearly shows the effect of detention period on BOD removal. In view of the fact that high raw waste BOD concentrations are associated with long detention times at any BOD loading, some general conclusions can be drawn from these results. These will apply within the limits of the variables studied and are based on the assumption that pond pH, which was not reported in the original paper, was not an influencing factor. The results show that the effect of a long detention period at any particular loading was to give a higher areal BOD removal than at a short detention period. Also, at any particular detention period a high BOD loading gave higher areal and percentage BOD removals than a low BOD loading. This increasing BOD removal efficiency with increasing loading has important practical implications. Although individual points at low BOD loadings do not fit the curves exactly, BOD removals in 2nd, 3rd and 4th stage ponds seem to be consistent with the trends for 1st stage BOD removals. It appears, therefore, that maintaining high BOD loading rates on all stages of anaerobic pond will give the highest BOD removal efficiency, as well as most economical land use.

Results collected by ALIVIO (1968) in anaerobic pond studies in Bangkok, using synthetic sewage as influent waste to 3 ft deep experimental ponds, are presented in Figure 4. Although gross interpolation was necessary in the figure, and there is no justification for using individual points for practical design, the trends suggested by the few data collected can be of general use. As with Parker's results, Figure 4 indicates that increased detention time at any BOD loading gives increased BOD removal but the effect is more dramatic at high BOD loading levels. Likewise the results suggest that at any detention period the highest BOD removal would result from the highest BOD loading. It is also interesting to note the close agreement of points for the 200 mg/1 influent BOD in this figure with Parker data presented in Figure 3.

UDDIN (1970) carried out a study of anaerobic pond treatment of tapioca starch waste in 3 ft deep experimental ponds and obtained the results shown in Figure 5 at steady-state conditions. Four replicated ponds receiving waste with average BOD 3800 mg/1 and loaded at 6160 lb/acre day with 5 days detention period gave a mean areal BOD removal rate of 3570 lb/acre day (standard deviation 70 lb/acre day). The two lines have been drawn on Figure 5 to represent approximate BOD removals for areal BOD loadings of 6000 and 4000 lb/acre day. It will be noted that a BOD loading near 6000 lb/acre day gave maximum BOD removal at nearly all detention times. This can be explained when reference is made to Figure 6 showing the respective pH levels in the ponds at the various loading rates and detention times. At BOD loadings greater than 6000 lb/acre day, with this particular waste, effluent pH dropped below 6.0 in most ponds which certainly affected performance. The exception is a loading of 7700 lb/acre day at 2 days detention time which maintained a pH of 6.3 and gave a better BOD removal than the loading of 6020 lb/acre day at the same detention time. In spite of the fact that pH was an influencing variable in this study, the trend of the data confirms that increasing detention time, up to 5 days for

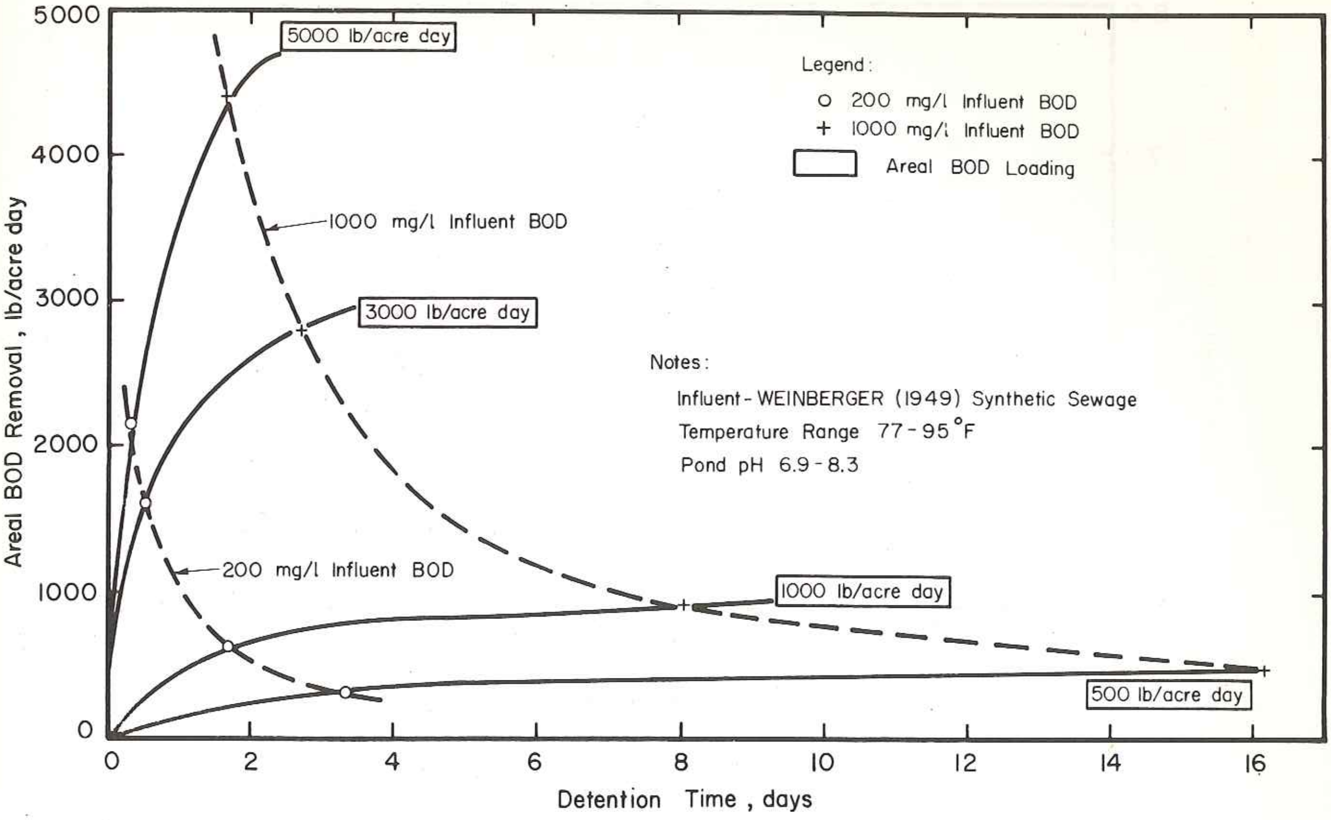


Figure 4. - Effect of detention time on BOD removal in anaerobic ponds (after alivio, 1968)

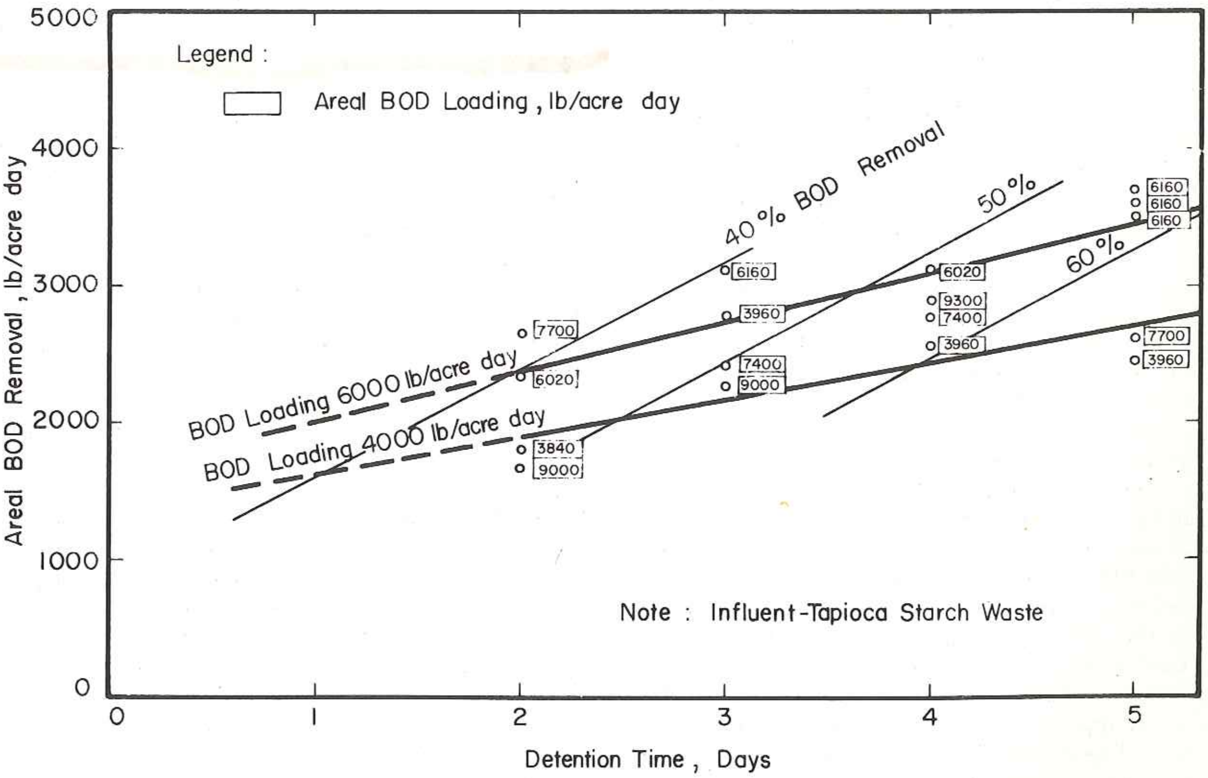


Figure 5. - Effect of detention time on single-stage anaerobic pond performance

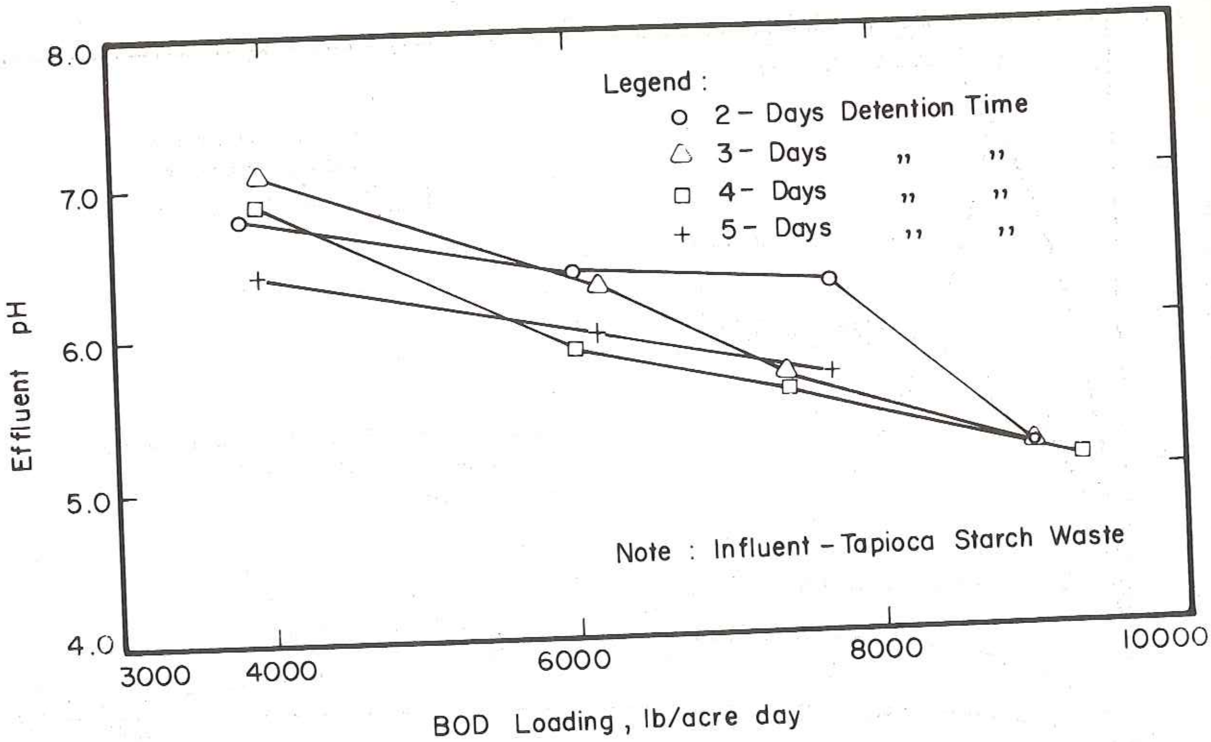


Figure 6. - Effect of BOD loading on anaerobic pond effluent pH.

this waste, at a particular BOD loading will result in increased BOD removal. Also, until pH became the limiting factor, apparently at levels below 6.0, increasing BOD loading gave improved areal BOD removal at any detention time between 2 and 5 days. If Uddin's results are compared with those of Parker and Alivio it will be seen that the trends are similar with the exception that the effect of pH on pond performance is significant. It would appear that the higher temperature in the tropics allows anaerobic fermentation to proceed at a rapid rate at pH levels down to 6.0, which is lower than the minimum practical limit suggested by OSWALD (1968).

The results reported are too few on which to base a formulation of the effect of detention period on anaerobic pond performance at the present time, but do enable general conclusions to be drawn. Increased detention time at any particular BOD loading results in increased BOD removal efficiency, the magnitude of the increase being greatest at high loadings. The highest possible areal BOD loading at any particular detention period will give the greatest areal BOD removal efficiency, providing pond pH does not become limiting. Strictly speaking, it can only be stated that this will apply within the range of detention times covered in the tests. In practical terms, for anaerobic pond treatment of a waste with a particular BOD concentration, applying the raw waste at the maximum areal BOD loading which will permit pond pH to remain above 6.0 in the tropics will give the highest areal BOD removal efficiency, always assuming odour is not a consideration. Waste dilution through recirculation or other operational technique will reduce detention time and hence can be expected to adversely affect areal BOD removal.

Series Operation of Multi-Stage Anaerobic Ponds

Three stages of 3 ft deep experimental anaerobic ponds were operated by UDDIN (1970) in the treatment of tapioca starch waste, with an average BOD concentration of 3800 mg/1, under four loading systems, the equivalents of which are shown diagrammatically in Figure 7. A summary of his performance results is given in Table 3, which includes average loading and removal rates for multiple stages of ponds in series. Comparing system I with systems II, III and IV in Table 3, it can be seen that the effect of the higher 2nd stage areal BOD loading was to give a much higher areal BOD removal and a slightly higher removal efficiency, in spite of the lower detention time. A comparison of 2nd stage areal BOD loading was to give a much higher areal BOD removal and a slightly higher removal efficiency, in spite of the lower detention time. A comparison of 2nd stage areal BOD removals with first-stage areal BOD removals for systems II, III and IV show that even at a slightly higher areal BOD loading, the removal was lower. However, it seems the lower areal BOD removal was due not to the fact that the organic matter became less amenable to breakdown (decreasing K value) after passage through the first stage pond, but to the lower detention time in the 2nd stage ponds. The BOD removal of 2560 lb/acre day in the 2nd stage ponds in systems II, III and IV is consistent with that to be expected from Figure 5 at a detention period of 2 days. In system I, 2nd stage BOD removal was lower than would be predicted from Figure 5

Table 3 — BOD Removals in Series Anaerobic Ponds

System	Pond Stage	Area, acre	Detention Time, days	Input		Output		BOD Removal	
				BOD lb/day	BOD Loading lb/acre day	Effluent BOD, mg/1	BOD lb/day	Areal, lb/acre day	Efficiency, %
I	1	1.47	5.0	9060	6160	1630	3860	3510	57.0
	2	1.00	3.4	3860	3860	1000	2430	1430	37.0
	3	1.00	3.4	2430	2430	530	1300	1130	47.0
	1+2	2.47	8.4	9060	3670	1000	2430	2690	73.2
	1+2+3	3.47	11.8	9060	2610	530	1300	2240	85.6
II	1	2.35	5.0	15580	6160	1520	6570	3680	57.8
	2	1.00	2.0	6570	6570	990	4010	2560	39.0
	3	3.34	4.7	4010	1200	630	2540	440	36.4
	1+2	3.53	7.0	15580	4410	990	4010	3270	74.2
	1+2+3	6.87	11.7	15580	2270	630	2540	1900	83.8
III	1	2.53	5.0	15580	6160	1520	6570	3680	57.8
	2	1.00	2.0	6570	6570	990	4010	2560	39.0
	3	4.18	5.5	4010	960	570	2300	410	42.5
	1+2	3.53	7.0	15580	4410	990	4010	3270	74.2
	1+2+3	7.71	12.5	15580	2020	570	2300	1720	85.3
IV	1	2.53	5.0	15580	6160	1520	6570	3680	57.8
	2	1.00	2.0	6570	6570	990	4010	2560	39.0
	3	6.90	9.3	4010	580	410	1650	340	58.6
	1+2	3.53	7.0	15580	4410	990	4010	3270	74.2
	1+2+3	10.43	16.3	15580	1490	410	1650	1335	89.3

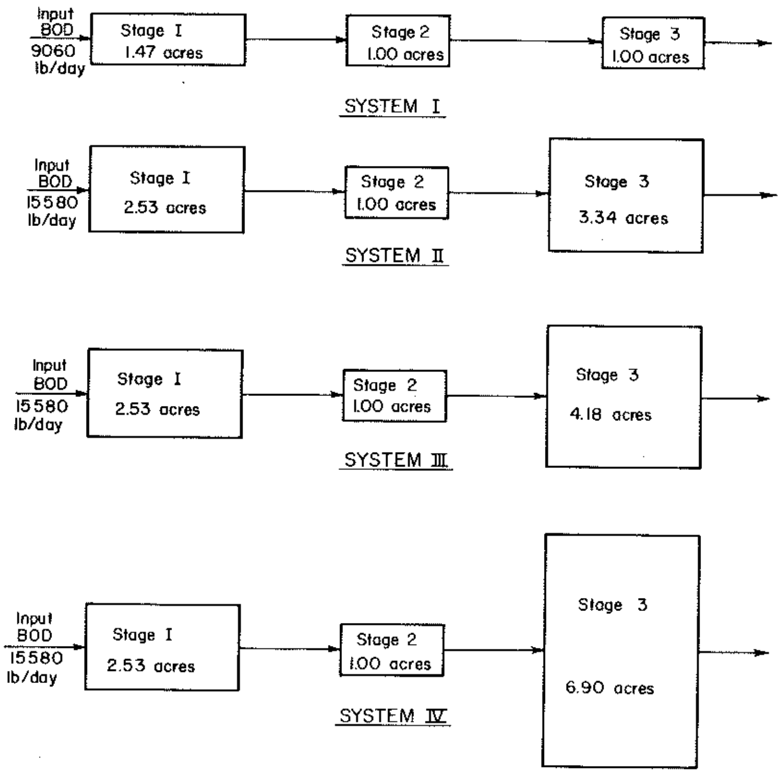


FIGURE 7.- EQUIVALENT SYSTEMS OF ANAEROBIC PONDS IN SERIES

Figure 7. - Equivalent systems of anaerobic ponds in series

for a detention period of 3.4 days, this implying either that the organic matter was becoming more difficult to degrade or that the difference was due to sedimentation of organic particles in the first stage pond. Further studies are being carried out to establish the true effect and cause. 3rd stage areal BOD removals are generally low due to low applied BOD loadings but an increasing efficiency of BOD removal is noted with increase in detention time, in spite of decreasing areal BOD loading. In systems III and IV, effluents from the 3rd stage ponds showed dissolved oxygen concentrations of 0.5 and 1.5 mg/1, respectively, at mid-day indicating that these ponds were operating at the lower loading limit of what might be termed anaerobic ponds or at the upper loading limit of facultative ponds since algae were present in the surface layer.

Plots of average areal BOD loadings, average areal BOD removals, and effluent BOD concentrations for the four systems of series ponds are shown in Figure 8. For the first two stages of ponds, average areal BOD removals were highest in systems II, III and IV, where average areal BOD loading rates were highest, although total detention times were less. However, system I gave the highest average areal BOD removal after three stages of ponds because of the higher average loading rate, even at a similar total detention time to those in systems II and III. System IV with the lowest average areal BOD loading gave the lowest average areal BOD removal although it produced a slightly better effluent. The average BOD removals in these systems may be compared with Alivio's results in Figure 4, where it will be seen that the removals are lower for this waste at any average areal BOD loading than for synthetic sewage at the same loading and detention time. This is probably a result of the lower pH in the case of the systems treating tapioca starch waste. Allowing for the effect of pH, the results suggest that the same order of removal can be obtained with lower BOD wastes and that the general trends would equally apply.

Recent results from series operation of multiple stage anaerobic ponds confirm the suggestion, previously mentioned in connection with Parker's data, that maintaining high BOD loading rates on all stages of ponds will give best areal BOD removal, and hence most efficient land use. If a constant high areal BOD loading is applied to each stage of anaerobic pond, then detention time in each stage will decrease from first to last stage and pond area will likewise decrease. This is a new practical concept which might well receive attention in future anaerobic pond systems design. Furthermore, it is postulated that stages after the first might well be loaded at areal BOD loadings of increasing magnitude, to maintain a high average areal BOD loading, because pH increases in passage through any stage allowing greater loadings to be applied. These suggestions are based on limited data and their applicability will be dependent on the ponds being operated at an average areal BOD loading within the capability of an anarobic pond system, the upper loading limit not being known at present, and at minimum detention times in later stages which do not limit the efficiency of BOD removal.

To illustrate the possibilities for treating 1 MGD of tapioca starch waste, with mean influent BOD concentration 3800 mg/1, in anaerobic ponds, the performance of the alternative prototype systems shown in Figure 9 have been estimated using Figure 5. Pond BOD loading was taken as 6000 lb/acre day until the required detention time in a stage became less than 0.86 days, necessitating undesirable extrapolation for estimation of BOD removal, when a loading of 4000 lb/acre day was adopted. System B with stepped addition of waste was introduced in an attempt to maintain minimum detention periods within the limits of the results in Figure 5 for as many pond stages as possible. It was assumed that the effluents from the anaerobic pond systems would be treatable in a facultative pond if a high quality effluent was required. The results are presented in Table 4, in which it can be seen that system A, with the total input flow applied to the first and subsequent ponds, was most efficient in removing BOD. The least area was required to give an average BOD removal of 2800 lb/acre day at an average BOD loading of 3000 lb/acre day. Stepped addition of waste in system B, in spite of allowing a BOD loading of 6000 lb/acre day to be adopted for 5 stages, gave less average BOD removal than system A. There is no doubt that a flow diagram and loadings similar to those adopted in system A would approach the best practical anaerobic pond treatment system for this waste. It is highly probable that a similar flow diagram with different loadings, appropriate to the particular waste being treated, would be generally applicable for anaerobic pond treatment of any waste. Further research is under way to fully justify this suggestion.

Odour from Anaerobic Ponds

Heavily loaded anaerobic ponds will undoubtedly produce odours, particularly if environmental conditions are suitable for the liberation of hydrogen sulfide. The cause of the odour emitted from anaerobic ponds is the release of hydrogen sulfide, ammonia, lower hydrocarbons and other organic compounds in gaseous form. Hydrogen sulfide equilibrium, which is pH dependent, is a critical factor in the production of odour in anaerobic systems. The effect of odours may be to limit the use of anaerobic ponds to remote areas, but this is less likely in developing countries. In tropical developing countries at the present time, very strong industrial wastes, such as those released from the processing of agricultural materials, will normally be producing odours because of irresponsible discharge without treatment. Organized and efficient treatment before discharge will be an improvement of general environmental conditions even if odours are produced in the process. The efficiency of the anaerobic form of pond in removing BOD is likely to be the main factor in deciding upon the type of treatment adopted by industry. Difficulty of land acquisition and efficiency of land use will often force municipal authorities to adopt anaerobic ponds for treatment of sewage in the tropics, recognizing that facultative ponds will be used for final polishing of the effluent. Therefore, if the assumption is made that anaerobic ponds will be widely used in tropical countries, the possibilities available for control of odours must be considered.

Control of odour can be accomplished by reducing pond loading to a point where dissolved oxygen begins to be present at the surface, through algal photosynthesis. Although the BOD loading level at which this occurs in the tropics is higher than in a temperate climate, its adoption will still limit the extent of land use efficiency. In Bangkok, UDDIN (1970) detected dissolved oxygen at the pond

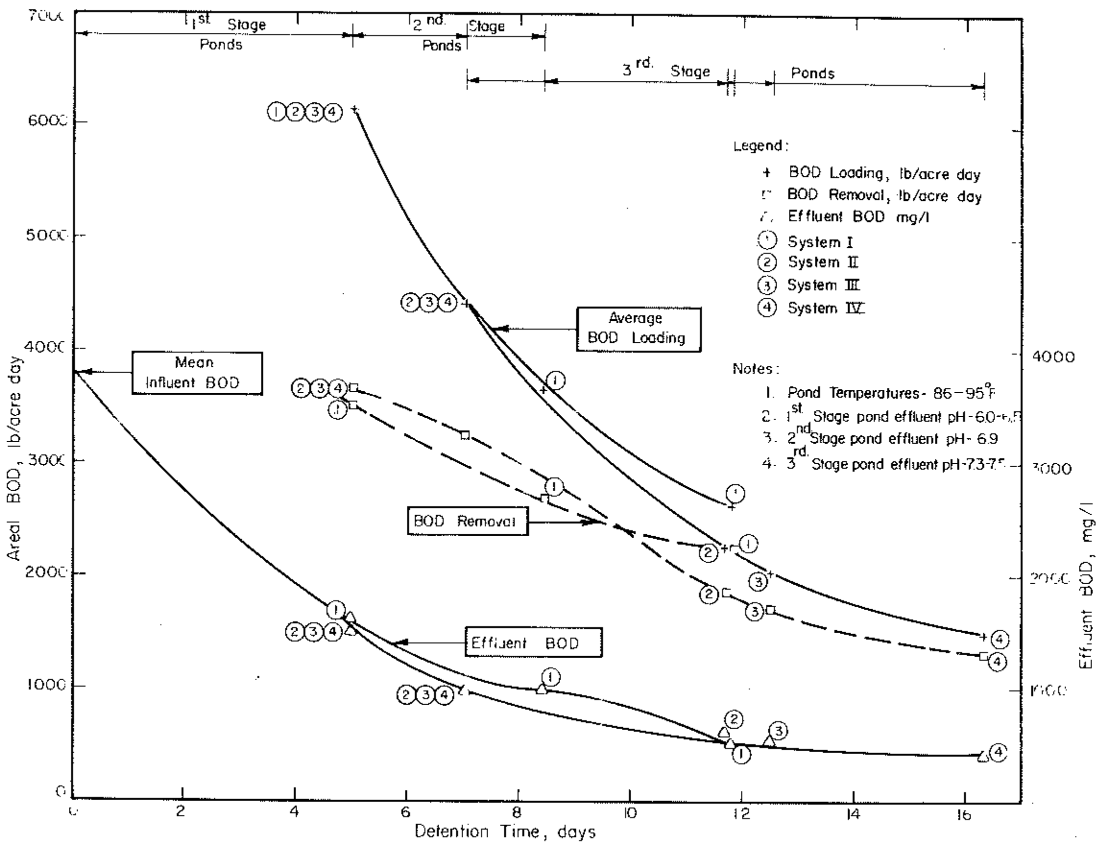


Figure 8. - Series operation of anaerobic ponds treating tapioca starch waste

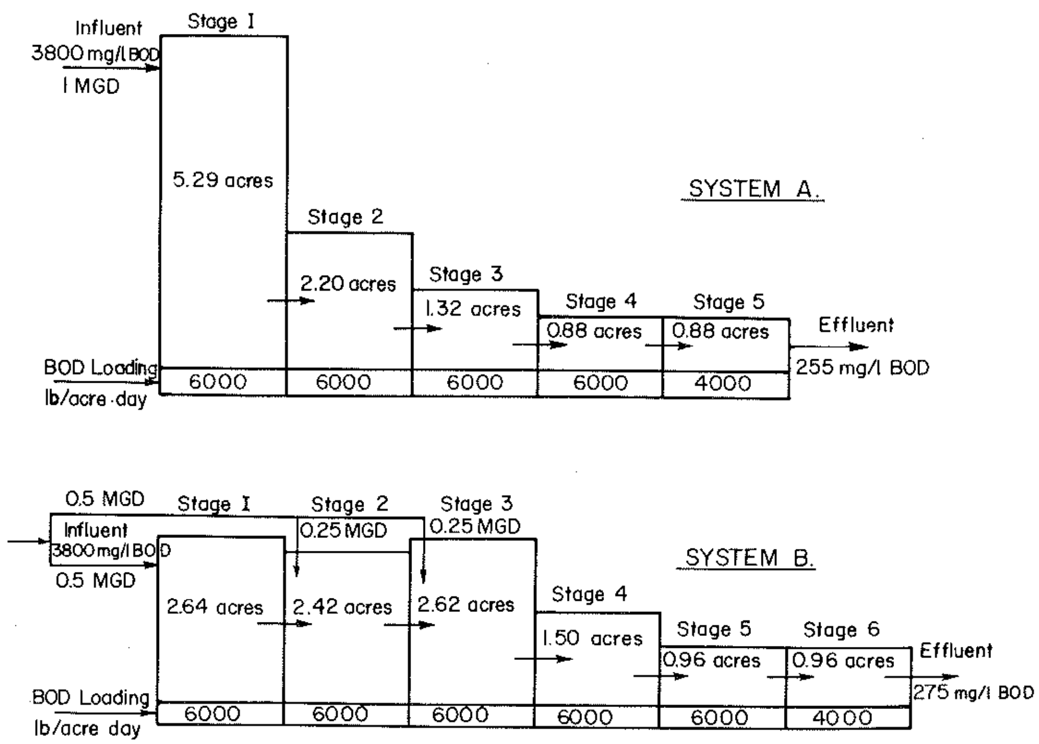


Figure 9. - Alternative anaerobic pond systems for tapioca starch waste treatment

Table 4 – Alternative Prototype Anaerobic Pond Systems for Tapioca Waste Treatment

Alternative System	Pond Stage	Input		Required Area, acres	Detention Time, days	BOD* Removal lb/acre day	Output	
		BOD, lb/day	BOD Loading lb/acre day				BOD lb/day	Effluent BOD mg/1 +
A	1	31,710	6000	5.29	5.18	3500	13,200	1580
	2	13,200	6000	2.20	2.15	2400	7,920	950
	3	7,920	6000	1.32	1.29	2100	5,220	625
	4	5,220	6000	0.88	0.86	1900	3.540	425
	5	3,540	4000	0.88	0.86	1600	2,130	255
	1+2+3+4+5	31,710	3000	10.57	10.33	2800	2,130	255
B	1	15,855	6000	2.64	5.18	3500	6,600	1580
	2	14,530	6000	2.42	3.16	2800	7,750	1240
	3	15,680	6000	2.62	2.56	2550	8,980	1080
	4	8,980	6000	1.50	1.47	2150	5,760	690
	5	5,760	6000	0.96	0.94	2000	3,820	460
	6	3,820	4000	0.96	0.93	1600	2,280	275
	1+2+3+4+5+6	31,710	2860	11.10	14.24	2650	2,280	275

*From Figure 5, for 3 ft deep ponds
+Assuming no evaporation or percolation.

surface only at BOD loadings of 960 and 580 lb/acre day, whereas a loading of 1200 lb/acre day gave completely anaerobic conditions. If odour was not considered, a BOD loading of 6000 lb/acre day could be applied. An areal BOD loading of about 1000 lb/acre day seems to provide a slight aerobic surface layer in the tropics and would be the limit of completely anaerobic operation.

Another important factor connected with pond loading is pH. Heavily loaded ponds will tend to have low pH and this is one environmental condition which allows release of hydrogen sulfide if the pond contains sulfur. The hydrogen sulfide-sulfide equilibrium is such that if pond pH is maintained above 8.0 the partial pressure of the small amount of free hydrogen sulfide present will be insignificant and odour problems will not occur. pH adjustment in combination with BOD loading limitation would be an effective means of preventing odours but would increase either land use or operational costs, or both.

An alternative form of odour control which has been used in anaerobic ponds is chemical treatment, sometimes in combination with surface aeration. CANHAM (1968) reported on the use of sodium nitrate in the canning industry, but the costs involved would normally be prohibitive for widespread use in developing countries.

The other measure which has been adopted to overcome odour problems in anaerobic ponds is recirculation. ABBOTT (1962) reported odourless operation at a BOD loading rate of approximely 5800 lb/acre day on the anaerobic pond of the anaerobic-aerobic pond system at Wynberg-Muizenberg, South Africa, when secondary aerobic pond effluent was recycled into the incoming sewage in the ratio 1 to 1. VAN ECK and SIMPSON (1966) reported primary anaerobic pond BOD loadings from 1692 to 5214 lb/acre day on the Chatsworth, Durban, South Africa ponds to give odourless operation in summer and winter when 38.8 to 13.9 percent of the effluent from the aerobic pond was recycled to the incoming sewage. KAMAL (1969) compared anaerobic pond system performance with and without recirculation at BOD loadings of 1500 and 2500 lb/acre day, not including recycled BOD, using synthetic sewage as influent with a BOD concentration of 200 mg/1. The highest BOD removal rate recirculation, for recirculation ratios between 5 and 100% of inflow. It seems likely, therefore that recirculation will be effective in suppressing odours in anaerobic pond operation if a facultative pond effluent containing dissolved oxygen is recycled but inevitably pond areal BOD removal will decrease. An exception to this might be if the recycled flow had a significantly higher pH than the influent flow to an anaerobic pond, because the influence of pH on areal BOD removal is greater than that of detention time. It should be relatively easy in tropical countries to maintain the recycled flow at the pond surface, particularly with deep ponds, because the effluent will normally be at a higher temperature than the influent.

FACULTATIVE PONDS

As the major purpose of facultative stabilization pond treatment is removal of organic material with minimum odour nuisance, the following discussion is not related to pathogen survival but primarily describes the development of design criteria for primary facultative ponds in tropical climates on the basis of BOD removal. In contrast with other forms of sewage treatment, the major proportion of the costs of treatment by ponds is associated with land requirements. It is natural for design parameters to reflect these requirements in preference to relating to volumetric measures, as in the case of conventional secondary treatment plants. It is for this reason that the areal BOD loading rate has come into widespread use as a design parameter. On the other hand BOD removals have largely been reported as percentages which has made the comparison of pond efficiencies difficult. The areal unit, lb BOD removal/acre day, used in conjunction with areal BOD loading reflects not only the efficiency of BOD removal but also of land usage.

Important external factors influencing the primary facultative pond process are areal organic loading, pond depth, detention period, temperature, solar radiation intensity, and the quantity and quality of influent waste. Although consideration has been given to the influences of detention period and temperature by MARAIS and SHAW (1961) and GLOYNA (1965) which resulted in suggested design formulations, little theory has been developed for other influencing factors. In comparison with other secondary sewage treatment processes the facultative oxidation pond is far more complex than its rather simple physical exterior suggests. Both anaerobic and aerobic phases within the pond are extremely complex involving both plants and a wide range of animal life. Several workers have studied pond systems in a rational way such as SUWANNAKARN (1963), SHAW *et al.* (1962) and MARAIS and SHAW (1961). Few researchers have concentrated on principles involving the fundamental interactions and relationships between biological phases within the facultative pond, as has OSWALD (1957).

A review of the literature pertaining to both tropical and temperate facultative oxidation pond research and experience has been carried out. Although the separate influences of the more usual design criteria (areal BOD loading, pond depth, detention period and temperature) are difficult to define clearly, each is discussed below.

Areal BOD Loading of Facultative Ponds

Data collected from primary facultative ponds operating under 143 different conditions have been collated and analyzed. In general, BOD removals in these ponds remained within the range of 70 to 90% (mean 79.4%, standard deviation 7.2%). Notable exceptions to this generalization were ponds located near Lebanon, Ohio operated at areal organic loadings in excess of 100 lb BOD/acre day (HORNING *et al.*, 1964). The influence of areal loading on areal BOD removal my be visualized using Figure 10*. Little scatter of data occurs about the regression line:

$$L_r = 9.23 + 0.725\ L_o \qquad (2)$$

(Standard Error of Estimate 14.9 lb BOD/acre day)

where, L_r = Areal BOD removal, lb/acre day, and
L_o = Influent Waste BOD, mg/1

This regression equation has a very high correlation coefficient of 0.995 and a 95% confidence interval of ± 29.3 lb BOD/acre day removal. It was expected that the regression line would pass though the intersection of the axes, which prompted a second regression analysis to be performed with the line passing through the origin. The resultant error estimate was larger than before, the correlation coefficient being 0.95, Equation 2 is preferred for estimation of expected BOD removals at any loading between 30 and 500 lb BOD/acre day.

A rather startling suggestion which this analysis reveals is that BOD removal in facultative ponds may be independent of pond depth, detention period, and influent waste concentration. The effect of temperature also appears to be minimized, but it is to be noted that temperatures were not evenly distributed over the range of loadings, higher ambient temperatures being associated with higher loadings.

Effect of Detention Period on Facultative Pond Performance

The effect of detention period on areal BOD removal is shown in Figure 11; but, unfortunately, this effect is confounded with that of areal BOD loading. Indeed, the sudden rise in removal rate at low detention times is quite contrary to expectations and is possibly due to the effect of high BOD loadings at reduced detention periods. As organic loading has been shown to have considerable effect on areal removal it is postulated that detention period has little significant influence on removal. These data were analyzed in terms of percentage BOD removals in an attempt to reveal the separate effect of detention period. The influence of varying temperature was avoided through partitioning the data into ambient temperature ranges. Where sufficient temperature data were not available, the corresponding pond observations were omitted from the analysis. Under the assumption that confoundment of temperature and detention period effects were removed by data partitioning, Figure 12 should give a reasonably clear and independent evaluation of detention period effects. Regression equations and relevant statistics are listed in Table 5. Detention period appears to affect percentage BOD removals, however in view of the wide scatter of data about other regression lines this could only be proven within the 50 to 60°F temperature range.

O'CONNOR and ECKENFELDER (1960) have utilized the monomolecular equation as a basis for aerated lagoon operation as have MARAIS and SHAW (1961) for primary facultative ponds in central and southern Africa. Based on the assumption that ponds are completely mixed by natural (MARAIS, 1966) or artificial (O'CONNOR, 1960) means a materials balance may be performed as follows:

$$L_a\ Q - L_e\ Q = (K\ L_e)\ V \qquad (3)$$

where, L_e = Concentration of effluent BOD, mg/1
L_a = Concentration of influent BOD, mg/1
Q = Rate of influent flow, ft^3/day
V = Pond volume, ft^3
K = Reaction rate constant to base 10, day^{-1}

which may be expressed as:

$$L_e/L_a = 1/(1+KD) \qquad (4)$$

$$\text{or } L_a/L_e - 1 = KD$$

MARAIS and SHAW (1961) adopted Equation 4 for primary facultative oxidation pond design in central and southern Africa and gave a tentative value of K = 0.17.

To study this theory over a wide range of pond conditions, values of $L_a/L_e - 1$ were regressed against detention period for each range of temperature. The slopes of least squares regression lines passing through the origin were best approximations of K values in each case. Plots of data revealed wide scatter as is indicated by the confidence intervals listed in Table 6.

If detention period strongly influenced BOD removal in

Table 5 – Regression Statistics of Relationships between BOD Removals and Pond Detention Periods

Temperature Range °F	Regression Equation	Correlation Coefficient	Std. Error of Estimate	No. of Data Points
0-30	$P=70.1+0.30\ D^{*+}$	0.443**	5.45	9
30-40	$P=76.8+0.24\ D^{+}$	0.421**	4.95	8
40-50	$P=64.3+0.41\ D^{+}$	0.436**	12.19	9
50-60	$P=71.3+0.28\ D$	0.469	5.48	17
60-70	$P=77.4+0.20\ D^{+}$	0.324	6.36	34
70-80	$P=79.3+0.11\ D^{+}$	0.326	6.05	22
80-100	$P=75.1+1.30\ D^{+}$	0.651	6.90	22

* where, P = Removal of BOD through pond, %
D = Detention period, days
** Correlation not proven significant (95% confidence)
\+ Effect of detention period on P not proven significant (95% confidence)

Table 6 – Evaluation of Reaction Rate Constants for Facultative Ponds

Temp. range °F	Rate Constant K, day^{-1}	Std. Err. of Est.	95% Confidence Interval	Number of Data Points
0-30	0.146	1.40	± 3.2	9
30-40	0.190	1.86	± 4.4	8
40-50	0.135	2.60	± 6.0	9
50-60	0.144	1.60	± 3.4	17
60-70	0.225	6.86	±13.4	34
70-80	0.162	5.27	±11.0	22
80-100	1.604	5.89	±12.2	22

facultative ponds, as Equation 4 suggests, only a slight scatter about regression lines would be expected. Such was not the case.

Based on the van't Hoff-Arrhenius relationship:

$$t/t_o = \theta^{(T_o - T)} \qquad (5)$$

where, t = Required reaction time, days at temperature T, °C
t_o = Base reaction time, days at temperature T_o, °C, and
θ = Temperature coefficient

GLOYNA (1965) has developed a pond design formulation utilizing a pond detention period of 3.5 days at 35°C as a base optimum achieving 90% BOD reduction. Hence, using D to represent detention period:

$$D = 3.5\ \theta^{(35-T)} \qquad (6)$$

Assuming that the required detention period is proportional to influent waste BOD concentration, a straight line factor $L_a/200$ was introduced into Equation 6, where L_a is influent BOD and 200 mg/1 was considered to be the average BOD value of sewage in the United States, giving:

$$D = 3.5\ \theta^{(35-T)}\ L_a/200 \qquad (7)$$

using, $D = V/N_pQ$
where, V = Volume of pond, acre ft
Q = Sewage flow, US gal/day
N_p = Number of people served

then, $$V = CN_p\ Q\ L_a\ \theta^{(35-T)} \qquad (8)$$

where, $C = 5.37 \times 10^{-8}$, a constant adjusting units and incorporating the ratio 3.5/200

Equation 7, being the source of Equation 8, was used to calculate theoretical detention periods for operating ponds which have been reported to achieve 85 to 95% BOD removals. The standard deviation of differences between actual and theoretical detention periods, as calculated using Equation 7, was 16.1 days and 95% confidence limits ± 31.5 days.

The monomolecular and van't Hoff–Arrhenius relationships are recognized to have possible application to many sewage treatment processes. However, the complexity of oxidation pond symbioses suggests that formulations based only on these principles utilizing detention period, temperature and rate constants as the most influential operating parameters are not likely to represent pond processes over a wide range of operating conditions. A resort to simplified relationships derived from basic principles may have some value when applied to a limited range of conditions but there is some danger that unjustified extrapolations of these relationships will be used by design engineers in the field.

Importance of Depth in Eacultative Pond Operation

Reports on studies of the effects of depth are scarce. The effects of depth variation are likely to be confounded

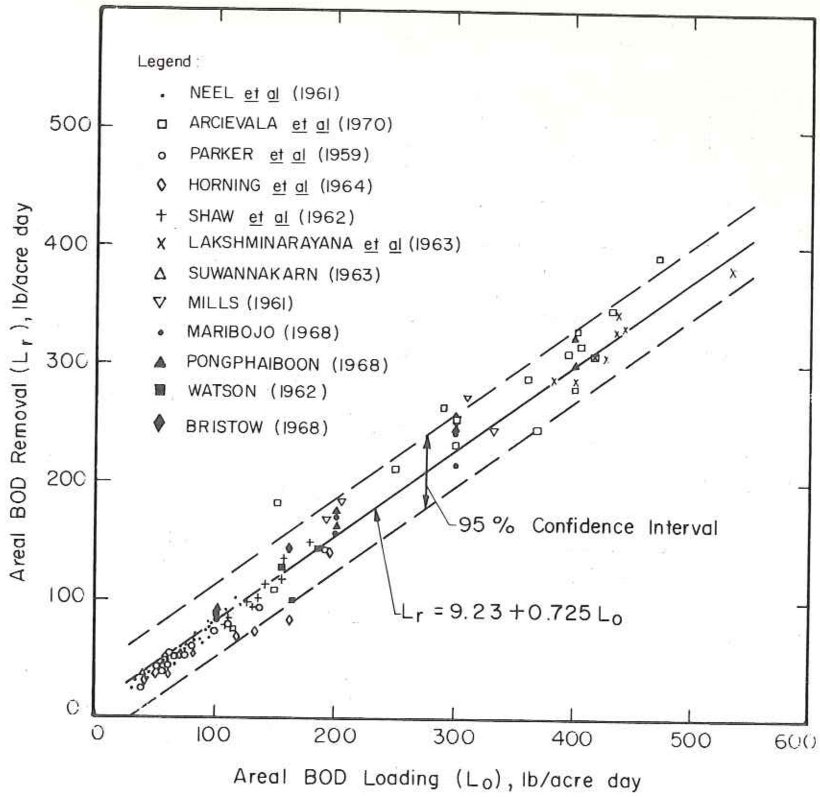


Figure 10. - **Areal BOD removal as a function of BOD loading**

*Unpublished Indian CPHERI data provided through kind permission of A. C. Arcievalla, CPHERI.

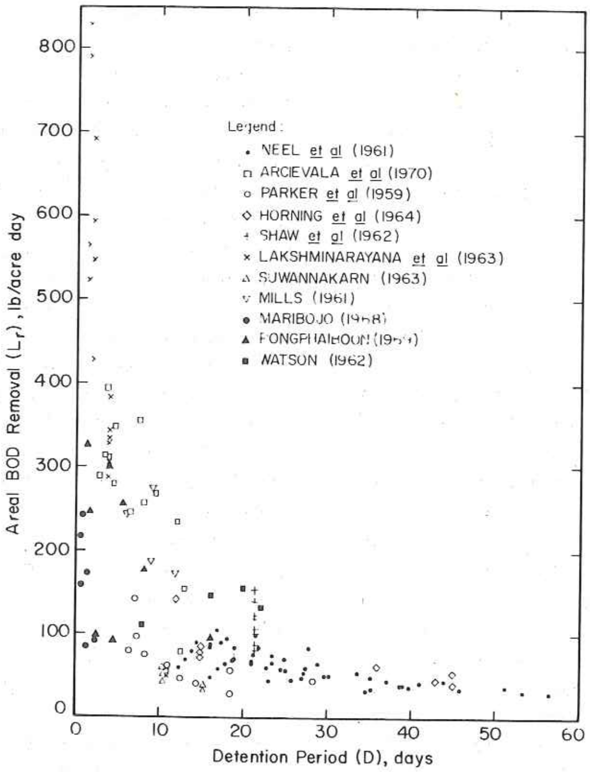


Figure 11. - **Pond detention periods and areal BOD removals**

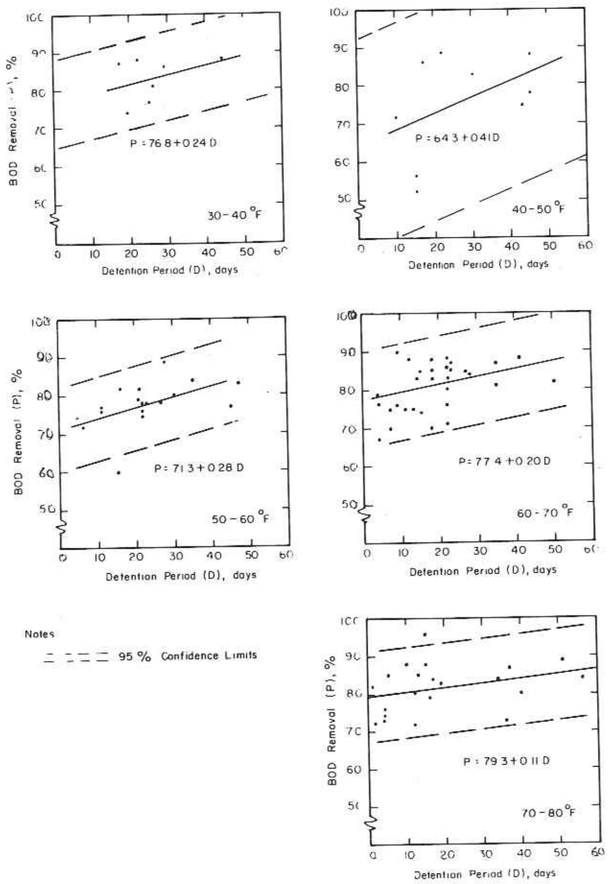


Figure 12. - The influence of detention period over % BOD removal in facultative ponds

with those of detention period. Under constant influent flow conditions a pond's depth change will effect a proportional change in detention period. MILLS (1961), using experimental ponds at 2.5 and 3.5 feet, found that pond depth had no effect on pond operating efficiency. Likewise PONGPHAIBOON (1968) observed no significant effect of depth variation from 0.83 to 3 ft on BOD removal efficiencies at areal BOD loadings of 100, 200 and 300 lb/acre day.

As part of the High Rate Pond Research Program at the Asian Institute of Technology, HSU (1970) conducted research into the individual effects of depth (10 to 18 in.), detention period (0.5 to 1.5 days), and areal BOD loading (200 to 400 lb/acre day) on pond performance. Separation of effects was accomplished by complete control of influent sewage concentration, flow and pond depth. Twenty seven pond conditions were evaluated using the experimental ponds and dosing apparatus shown in Figure 13. Although the ranges of levels studied apply to high rate pond operation, trends of effects are applicable to facultative ponds. Figure 14 describes the efficiencies of BOD removal in the experimental ponds and it can be seen that depth exhibited no significant influence. As might be expected from the preceding discussion, detention period had only a slight effect on BOD removal, there being no significant difference in removals between 1 and 1.5 days but some loss in efficiency at 0.5 days. As previously observed through the analysis of facultative pond operation, areal BOD loading had by far the strongest influence. Choice of pond depth should be guided by such considerations as mosquito prevention and protection of the lower anaerobic layer, and not BOD removal. It is generally considered that three to five feet is an appropriate facultative pond depth range for tropical conditions.

Influence of Temperature

Areal BOD loading in lb/acre day has been used as an important empirical pond design criterion for decades. Choice of a particular design value has depended upon field experience in any particular location. The effect of temperature on feasible loading rates has not been throughly investigated and applied to design standards on a world wide scale. A review of the literature pertaining to both temperate and tropical climates has revealed that considerably higher loading rates are possible than are currently being used. 'Climate' is herein defined in simplified but quantitative form as the mean monthly ambient temperature, representing both pond water temperature and incident solar radiation. Reported data were analysed in terms of mean monthly ambient temperatures which were readily obtained from ENVIRONMENTAL SCIENCES AND SERVICE ADMINISTRATION (1967).

Primary facultative pond failure is considered to occur when the pond reverts to an anaerobic state throughout the day at all depths. The data were analyzed to reveal maximum feasible pond loading up to the point of failure at any given temperature of operation, the results being shown in Figure 15. In some instances the month of pond

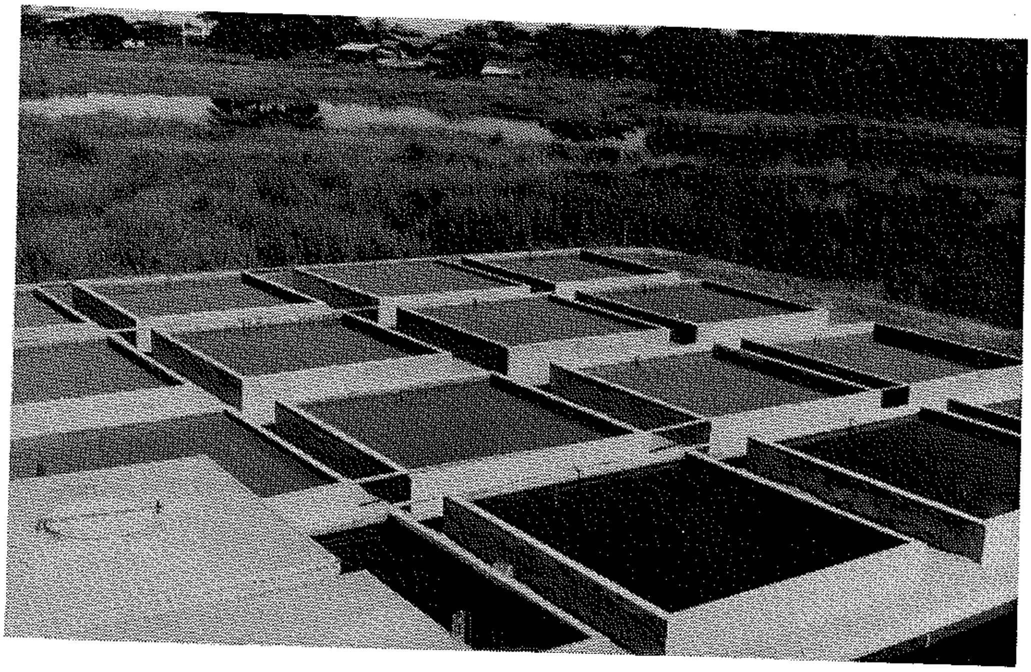
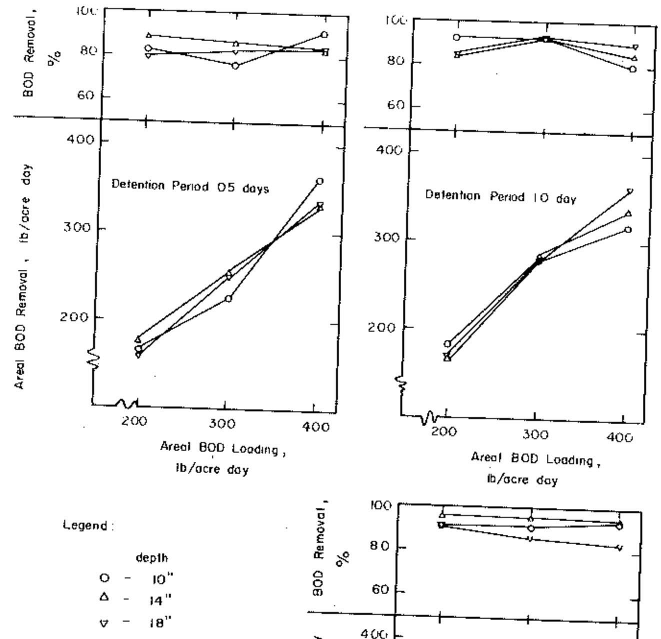


Figure 13. - Experimental Oxidation Ponds used in the study of Depth, Detention Period and Areal BOD Loading Effects.



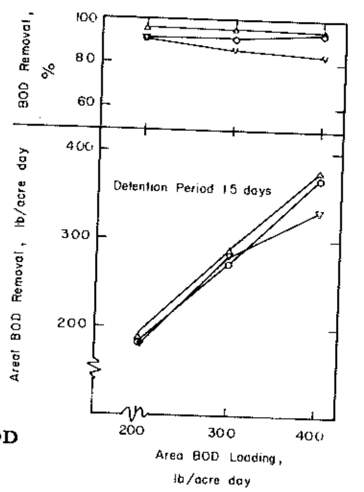


Figure 14. - Effects of depth, detention period and areal BOD loading on pond BOD removal

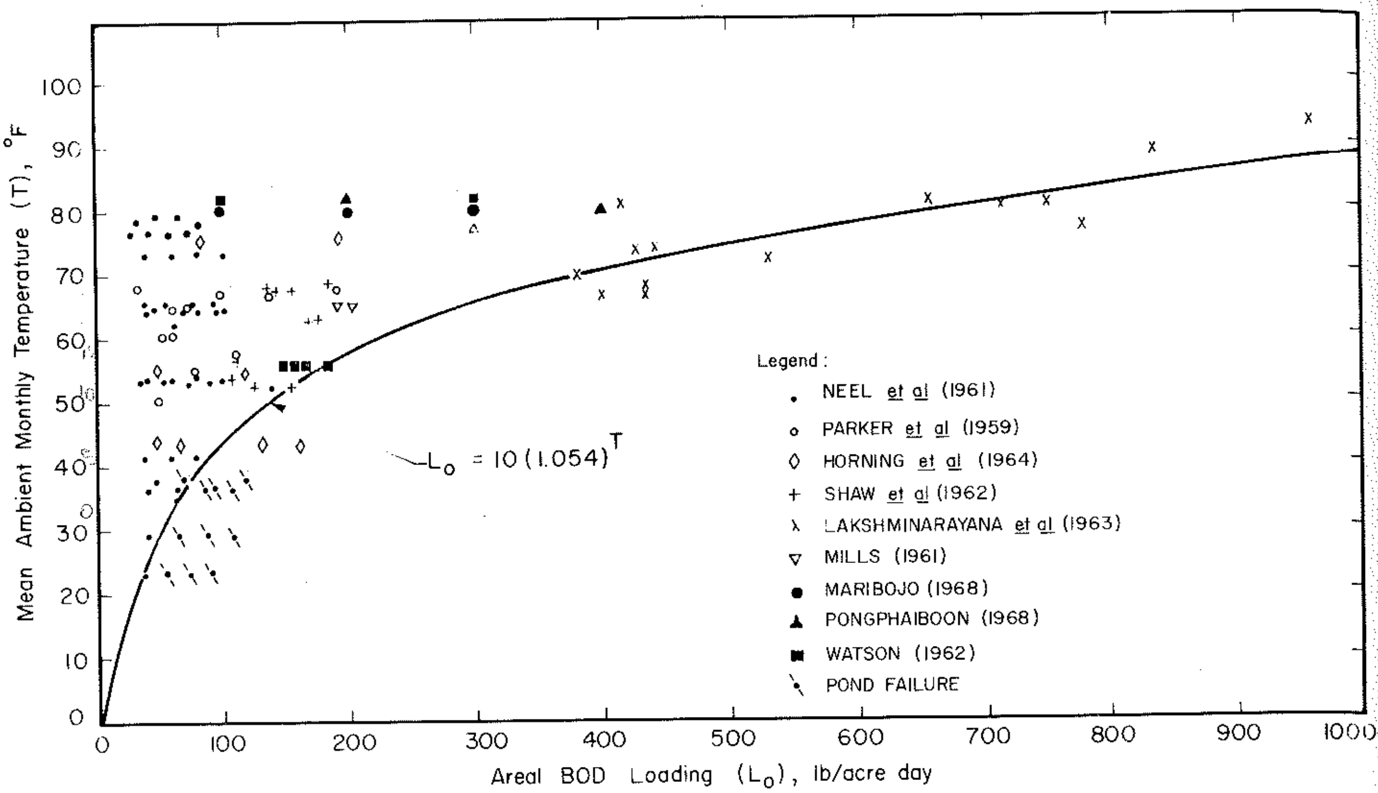


Figure 15. - Feasible facultative pond loading as a function of temperature

operation was not given in the literature, however, if the pond was reported to have operated successfully throughout the year the minimum mean monthly temperature was taken as the pertinant operating temperature. An appropriate mathematical model was designed to represent boundary conditions as the point of pond failure as shown in Figure 15. This equation describes the relationship between possible areal BOD loading and ambient monthly mean temperature in the range 20-90° F:

$$L_o = 10(1.054)^T \qquad (9)$$

where, L_o = Areal BOD loading, lb/acre day
T = Ambient mean monthly temperature, °F

This equation appears to resemble the van't Hoff-Arrhenius relationship ($\theta = 1.054$). At high loadings, tropical ponds often tend to maintain a relatively shallow algal-laden aerobic surface layer. Provided this situation is stable, these ponds achieve high rates of biodegredation in the lower anaerobic layers while odours are prevented from escaping through the aerobic surface which acts as a protective layer. This situation is desirable in view of the high stabilization rates achieved by contact anaerobic stabilization.

The boundary curve of Figure 15 approximates operation when the algal layer is just capable of maintaining aerobic conditions at any given temperature. Under these conditions it is likely that all oxygen produced by algae is utilized in oxidation. It is natural that algal production of oxygen is strongly influenced by temperature and solar radiation as reflected by the monthly mean temperature. In fact, Equation 9 suggests that algal oxygen production follow an Arrhenius type equation such that the oxygen produced by algae under high loadings increases by a factor of 1.42 for each ten degree (° F) rise in temperature. It should be emphasized that although Equation 9 may be of the Arrhenius form it is empirical, based on actual data collected in the field, and as such is of considerable value in design. Use of this relationship and Equation 2 in pond design permits estimation of allowable areal loading and expected BOD removal for any given location.

On the basis that the most efficient pond is one which removes the greatest quantity of BOD per unit area, ponds should be loaded to their maximum capacity as indicated by equation 9 for efficient land use and reduced capital cost. By maintaining these rates on primary, secondary and tertiary facultative ponds, subsurface anaerobic conditions will foster high rates of degredation. This implies that ponds should be decreased in surface area along a series of staged facultative ponds and is an extension of the conclusion arrived at for operation of anaerobic ponds in series.

CONCLUSIONS

Anaerobic Ponds

1. Areal BOD loading is the variable having greatest influence on areal BOD removal in anaerobic ponds, with the effects of influent pH and detention period being less significant.
2. The adoption in tropical countries of the maximum areal BOD loading which will permit pond pH to remain above 6.0 when raw waste is fed to anaerobic ponds will result in greatest areal BOD removal.

3. Maintaining maximum areal BOD loading, within the capabilities of the anaerobic system, on each stage of anaerobic pond in a series system will give the highest average areal BOD removal and most efficient land use.
4. Recirculation of a facultative pond effluent containing dissolved oxygen is likely to be effective in suppressing odours in anaerobic pond operation in the tropics but will result in a decrease in overall areal BOD removal.

Facultative Ponds

5. A survey of pond operation in tropical and temperate zones has indicated that the areal BOD removal (L_r, lb/acre day) in primary facultative ponds may be estimated through knowledge of areal BOD loading (L_a, lb/acre day) by the formula:

$$L_r = 9.23 + 0.725\ L_o$$

Standard Error of Estimate 14.9 lb/acre day

6. Within normal operating ranges, detention period and depth have little influence on percentage or areal BOD removal in a primary facultative pond.
7. Most economic primary facultative pond operation is achieved by applying maximum areal BOD loading up to the point of pond failure.
8. Excessive pond loadings result in failure through reversion to completely anaerobic conditions. Maximum feasible pond BOD loadings are related to environmental conditions as reflected by the mean monthly air temperature (T, $^\circ$F) during operation at any given location according to the equation:

$$L_a = 10(1.054)^T$$

Anaerobic-Facultative Pond Systems

9. To achieve most efficient land use, each stage of anaerobic and facultative pond in a series system should be loaded at the maximum possible areal BOD rate. This will result in decreasing pond areas along the series system.

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SURVIVAL OF ENTERIC BACTERIA AND VIRUSES IN MUNICIPAL SEWAGE LAGOONS

L. W. Slanetz, Clara H. Bartley, T. G. Metcalf, and R. Nesman
Department of Microbiology, University of New Hampshire, Durham, New Hampshire 03824

There is limited information in the literature on the fate or survival of enteric bacteria and viruses in oxidation pond systems and on the presence and numbers of these organisms in effluents from such ponds. The majority of the reports published to date have been concerned chiefly with coliform reduction or die-off. Okun (1) reported 99.99 percent reduction of coliforms in each of five experimental ponds when loaded with up to 100 pounds of BOD per acre per day. Drew (2) found maturation ponds to reduce *Escherichia coli* 99.6 percent in summer and 96.8 percent in winter. Coetzee and Fourie (3) report a 99.98 percent reduction of *E. coli* in stabilization ponds and because of the apparent ease with which it is eliminated, they consider this organism may not be an infallible indicator of pathogenic organisms in such pond effluents. This point of view was also expressed by Malchow-Moller, *et al* (4) who considered *Streptococcus faecalis* and *Clostridium welchii* more reliable indicators of pathogens than *E. coli* in the systems they studied. Gann, *et al* (5) found coliform reduction closely associated with BOD removal indicating that the coliforms are removed because of their inability to compete successively for nutrients. Geldreich, *et al* (6), in a study of raw sewage and effluent from a waste stabilization pond located at a state prison dairy farm, reported a reduction in coliform bacterial density from a low of 85.9 percent in the winter to a high of 94.4 percent in the autumn. Fecal coliform reductions were greater than 87.9 percent while reductions of fecal streptococci were 97.4 percent or more.

There have been few reports in the literature on the die-off of pathogens in oxidation ponds. Costzee and Fourie (3) found the total reduction of *Salmonella typhi* in the effluent from two stabilization ponds operated in a series with detention periods of 20 days to be 99.5 percent. The reduction of *E. coli* was 99.98 percent during this same period. In heavily polluted water they found *S. typhi* more resistant to die-off than *E. coli.*

Using *Staphylococcus aureus* and *Serratia marcescens* as test organisms in dialysis tubing immersed in the aerobic zone of a lagoon with a detention time of 6 to 7 weeks, Conley, *et al* (7) found an almost complete die-off of these organisms in 36 to 48 hr. This was not the case in the deeper anaerobic zone.

In regard to the elimination of viruses, Malherbe, *et al* (8) using a model system of four ponds in series, concluded that the biological processes which improve the effluent chemically and bacteriologically were unlikely to alter the virus content so that virus removal depended on their adsorption to static surfaces, exposure to rays of the sun, or a retention beyond the normal survival time of the virus. Christie (9) found that field lagoons reduced the titre levels of polio virus from 10^5 to less than 10^3 units per ml.

With the increased use of lagoons or oxidation ponds as an economical method of domestic waste disposal in this