A Rotating Flighted Cylinder for Solid-Liquid Separation and Biological Waste Treatment

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ABSTRACT

A single device for solid-liquid separation and biological waste treatment was designed, built, and evaluated. The device, a rotating flighted cylinder, consists of a cylindrical tube which has a helically wound fin mounted perpendicular to the interior surface. When mounted at a slight incline (7 to 15 degrees) and slowly rotated (1 to 3 rpm), the device provides a mechanism to accomplish sedimentation between wraps of the fin. The settled solids are augered toward the upper end and discharged as a solids-rich stream. The fin surfaces, alternately exposed to the waste and the atmosphere, perform conversion of soluble organic matter to bacterial cells in a manner similar to rotating disk processes.

The solid-liquid separation aspect of the device was evaluated with respect to dilute dairy and swine manure slurries. The unit was demonstrated to be a non-plugging, low cost device for removal of settleable particles. It did not remove floating solids. The 24-inch unit was tested at flow rates of 1 to 10 gpm.

As a biological waste treatment device, the unit was evaluated for the treatment of dilute animal manure slurries and domestic sewage. The constituent removal efficiencies were similar to those achieved in conventional secondary sewage treatment plants. When analyzed, the rotating flighted cylinder performance was consistent with data previously generated for rotating disk processes. The fact that the rotating flighted cylinder eliminated the need for a subsequent sedimentation tank gave it a specific advantage.

Overall, the rotating flighted cylinder was demonstrated to be a simple, low cost, low energy-consumptive device for the treat-

ment of small domestic and agricultural waste flows. Where a temporary or seasonal treatment unit is needed, it has some particular advantages over conventional package plants.

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INTRODUCTION

Several alternative devices exist for the treatment of wastewater. These devices are to facilitate the release of water into the natural environment with a minimum of adverse effects or to facilitate re-use of the water. Systems for the treatment of small waste sources present special problems. Septic tanks and absorption fields are most commonly used; however, successful implementation is restricted to regions of suitable soil characteristics and to relatively dilute wastewaters. Wastewater treatment and disposal alternatives to be used in lieu of septic tanks are generally expensive, require considerable operator attention, and are highly energy-consumptive.

Waste treatment devices utilize two basic phenomena for solids removal and organic matter concentration reduction. They provide an opportunity for suspended solids to settle from the carriage water. An aerobic biological process is incorporated in which dissolved organics are used as an energy source by microorganisms. A further sedimentation process is used to remove the biological solids formed by metabolism of the dissolved organics.

This project was designed to evaluate an alternate scheme to accomplish these transformations. The scheme proposes a single device for both solid-liquid separation and aerobic biological treatment. This device, a rotating flighted cylinder (RFC), consists of a slowly rotated inclined cylinder with a helically wound fin mounted perpendicular to the interior surfaces.

The specific objectives of the project were as follows:

1. To evaluate the solid-liquid separation capabilities of various RFC sizes. Wastes of particular interest were dairy manure slurry, liquid swine manure, and domestic sewage.

2. To evaluate the oxygen transfer capabilities of an RFC at various hydraulic loading rates and rotational speeds.

3. To evaluate the overall waste treatment capabilities of an RFC-based system when treating domestic sewage and dilute dairy manure slurry.

CONCEPT OF THE ROTATING FLIGHTED CYLINDER

Several devices for solid-liquid separation have been developed. Glerum, Klomp and Poelma (1971) discussed such separation devices applied to pig slurries. However, these systems have high purchase and operation costs which make them impractical for small livestock operations.

Because of the advantages of solid-liquid separation in liquid manure systems and the high cost of present separation devices, work has been done to develop a separator at Oregon State University.

PHYSICAL CONCEPT

The concept has evolved as a series of circular weirs over which manure slurry flows. The weirs create a series of small settling basins with the weirs themselves as basin outlets. Solids settling from the flow are trapped in the basins. By moving the basins slowly up an incline, solids are dumped at the upper end of the incline along with whatever water has also been trapped.

The movement of the basin is physically accomplished in the design of the separator. The heart of the separator is a tube with a helical fin attached to the inside surface. By mounting this tube on an incline, the water encounters a physical structure similar to that shown in Figure 1. When the tube is slowly rotated, the basins are, in effect, moved up the incline.

The first experimental separator employing this concept used an 8-inch diameter, 57-inch long tube made of sheet metal which had a 2-inch high sheet metal fin attached to the inside in a helical configuration. There was a 2 1/4-inch spacing between successive wraps of the helix. This tube was mounted on a frame built so the incline could be varied between 7 and 20 degrees.

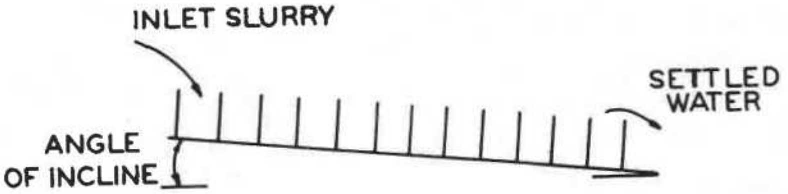

Figure 1. Physical structure encountered by the liquid phase in the rotating flighted cylinder.

The tube was rotated by an electric motor and a wormgear speed reducer. Tube rotation speed was varied between 1 and 3 rpm by the use of a series of different diameter pulleys. A sketch of the separator is shown in Figure 2 and the actual device in Figure 3.

THEORETICAL CONSIDERATIONS

The device is based upon a concept of settling in small tanks. Overall efficiency of the separator is controlled by the performance of the individual basins. Suspended solids removal of individual settling basins is controlled by three parameters: (a) turbulence of the fluid in the settling basin, (b) settling velocities of the solids being separated, and (c) detention time of the fluid in each settling basin.

The turbulence parameter is a function of flow rate, fluid viscosity, and incline of the basins. It is believed that the Reynold's Number for an open channel could be used as a measure of the turbulence of the parameter. It is not obvious whether the best measure of the parameter can be obtained by the Reynold's Number calculated using the flow area over the weir crest or through the settling basin.

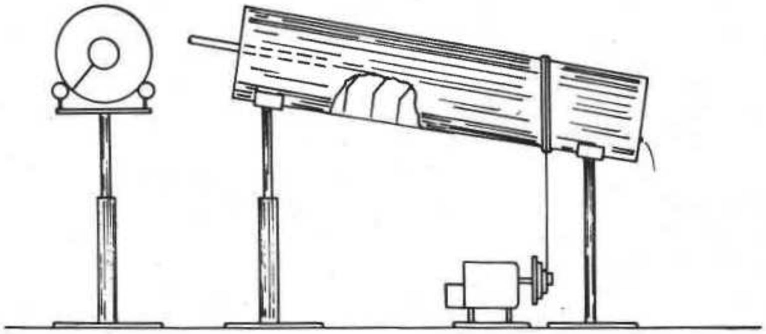

Figure 2. Sketch of the rotating flighted cylinder in operating position.

Information on the second parameter, settling velocities of manure particles, is not readily available. Due to the irregular shapes, variable sizes, and variable densities of the manure particles, settling velocities are impossible to predict. This parameter of the separation efficiency relationship, of necessity, will rely upon empirical data.

The third parameter, detention time of each individual settling basin, is a straightforward calculation dependent upon volume of individual basins and flow rate. Detention time is calculated by dividing basin volume by flow rate through the basin. The incline of the separation tube will slightly affect detention time but to an insignificant extent in the range of 7 to 20 degrees incline.

Development of the actual relationship between separation efficiency and the three parameters of turbulence, settling velocities, and detention time has not been completed. However, this analysis has been helpful in realizing certain design principles: (a) at the slopes being used (7 to 20 degrees), slope is of little importance, (b) flow rate is the single most important variable, and (c) the device is relatively insensitive to rotational speed in the range tested (1 to 3 rpm).

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PARTICLE MECHANICS

Sedimentation in the RFC can be theoretically described by considering each basin as an ideal settling tank and all solids as ideal discrete particles. All particles with a settling velocity, V_t, or greater will be completely removed when V_t enables the particle to fall a distance equal to the effective depth during the detention period in the basin.

$$V_t = y/T \qquad (1)$$

where: y = depth
T = detention time

Figure 4 shows the velocity analysis curve for discrete particles (Weber, 1972).

The function f(x) can be separated into the fraction of particles with $v_t \geq y_{max}/T$ and the fraction with $v_t \geq g(x)/T$ but $\leq y_{max}/T$.

$$n = (1 - f_t)VC \qquad (2)$$

where: f_t = fraction of particles with $V \leq V_t$
V = volume of the basin
C = concentration of particles

The proportion of remaining particles removed by sedimentation will be v_f/v_t where $v_f < v_t$ and the total number removed, n_t, will be:

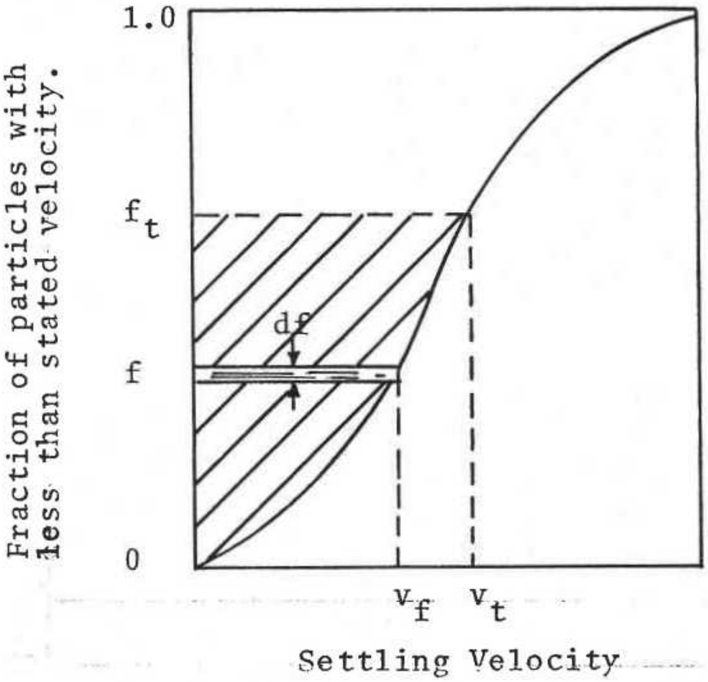

Figure 4. Settling velocity analysis curve for discrete particles (Weber, 1972).

$$n_t = n + VC \int_0^{f_t} v_f/v_t \, df \tag{3}$$

Since the depth of the RFC basin varies across its width, w, then v_t becomes a function of width (Figure 5).

$$v_t = \frac{g(x)}{T} = v_t(x) \tag{4}$$

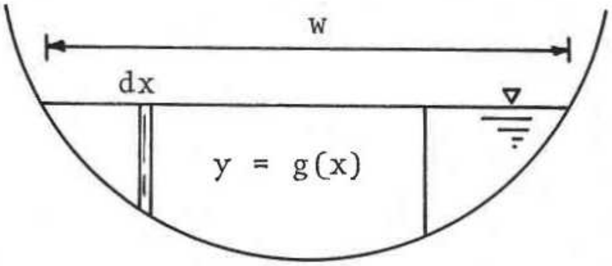

Figure 5. Cross section of RFC settling basin.

and f_t, in turn, also becomes a function of width.

$$f_t = f(x)$$

If n is the number of particles with $V \geq V_t$, which are completely removed, then the number of particles, n, with $v \geq v_t(x)$ is now expressed:

$$n = (1 - f(w/s))\ VC + aC \int_0^w (1 - f(x))\,g(x)\,dx \tag{5}$$

where: a = basin length

The proportion of remaining particles removed is now:

$$aC \int_0^w \int_0^{f_t} v_f/v_t(x)\ df\ g(x)\ dx \tag{6}$$

and the total number removed, n_t, is:

$$n_t = (a - f(w/s))VC + aC\int_0^w (1 - f(x))g(x)dx + aC\int_0^w\int_0^{f_t} v_f/v_t(x)\,df\,dx \qquad (7)$$

Under the stated conditions, all particles accounted for by the first two terms of Equation 7 would be removed in the first basin of the RFC and the remaining particles would be partially removed by each of the series of basins as indicated by the final term of the equation. This model is of use to give a qualitative description of the sedimentation potential of the RFC rather than any quantitative application. The successive removal of particles described by Equation 6 is a key parameter to solid-liquid separation in spite of the non-ideal conditions that actually exist.

Deviation from ideal conditions will create factors both enhancing and inhibiting to sedimentation of solids. Since ideal particles are discrete and non-flocculating, only the grit portion of municipal sewage can be considered to have truly ideal settling characteristics. The remaining solids can be classified under type 2 settling because they have a tendency to coalesce, or flocculate, during sedimentation (Metcalf and Eddy, 1972). As agglomeration among these particles occurs, their settling velocity increases; the larger particles create a reduced surface-area-to-mass ratio and thus, the drag forces opposing subsidence are reduced (Weber, 1972). This phenomenon expedites solids removal more efficiently than the model predicts; however, type 2 particles are subject to other forces that oppose proper settling. Since these particles have specific gravities much lower than grit, they are easily sheared and resuspended by turbulent forces.

Ideal conditions also presuppose that particles are initially equally distributed over the cross section of the tank. Although this is not true of particles entering the basin because entry is over a weir, the sloughing biomass particles are more uniformly distributed and a portion is already on the basin bottom.

Two other significant factors are short-circuiting and turbulence. The adverse effects of short-circuiting are reduced considerably by the numerous consecutive basins that must be passed through. It is apparent from observing the RFC in operation that a substantial portion of flow short-circuits across the top of each basin; however, there is a sufficient number of basins such that if a fraction of flow is dispersed in each basin, then virtually all the wastewater entering the cylinder will have spent non-short-circuited time in several basins. In addition, that portion of flow dispersed in each basin will experience a much longer detention time than the average detention time. Since most of the flow spends time in a number of basins, the chances of a particle experiencing an effective low overflow rate is increased.

EVALUATION OF THE RFC FOR SOLID-LIQUID SEPARATION

Several problems were encountered in testing the first experimental device. The first difficulty was development of representative sampling and analytical techniques. The sampling procedure was to catch all flow from the point being sampled (lower effluent, upper effluent, or influent) in a 265 ml plastic bottle. Solids in the sample were then separated into suspended and soluble portions by centrifuging. Suspended and soluble concentrations were obtained by drying and weighing the two portions and then dividing each weight by the volume, 0.265 l. This gave a solids concentration for the influent, lower effluent, and upper effluent in grams per liter. Since the separator can be expected to separate only suspended solids, the suspended solids separation efficiencies were calculated by dividing the lower effluent suspended solids concentration by the influent suspended solids concentration, subtracting from 1.0, and multiplying by 100.

The second problem encountered in evaluating the device was in providing a constant flow rate of a high solids content slurry at a flow rate compatible with the test unit. The use of small capacity pumps was unsuccessful because of frequent plugging. The use of a constantly overflowing, well-agitated tank was somewhat better but still not fully satisfactory. However, a series of runs was made using this agitated tank technique; both manure solids and beet pulp were fed. The beet pulp slurry, used to simulate manure solids, avoided many of the plugging problems.

The pumping problem was largely overcome by the use of a simple air-lift pump as shown in Figure 6. Manure slurry was pumped into a 55-gallon metal drum from the dairy manure storage tank using an open impeller irrigation pump. By regulat-

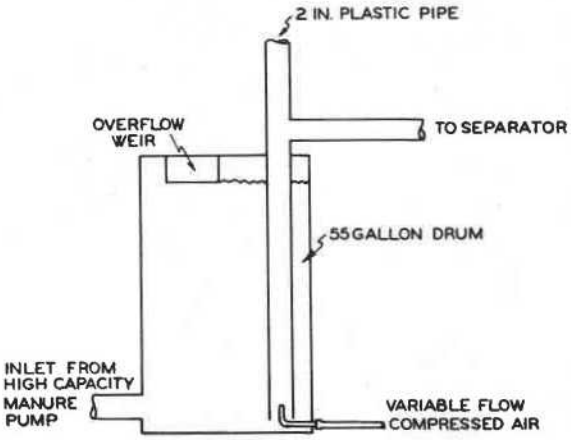

Figure 6. Air-lift pump used to feed slurry to the RFC solid-liquid separator.

ing output from a portable air pump, a steady flow of slurry was obtained with a minimum of plugging.

EIGHT-INCH TUBE

Trial runs using beet pulp slurry were helpful in determining operating characteristics of the separator. These data are summarized in Table 1. These runs established an optimum flow rate between 0.5 and 1.0 gpm.

When a manure slurry of approximately 0.4 percent settleable solids was run through the device at 0.5 gpm, settleable solids removals averaged 30 percent. This was considerably less than had been achieved with beet pulp. The difficulty resulted from the heavier particles remaining in the feed tank, never reaching the separator.

In evaluating these data, several observations were made: (a) the separator was operating satisfactorily in that no plugging or other mechanical problems were occurring, (b) the device was

Table 1. Percent suspended solids removal of the 8-inch separator receiving beet pulp slurry at three flow rates.[1,2,3]

	Flow rate, gallons per minute		
Time, minutes	0.50	0.75	1.20
10	58	42	33
20	40	55	33
35	61	72	35
50	71	46	73
70	60	44	48
90	66	89	11
120	65	57	--
150	78	65	--
180	70	41	27
210	72	60	--
Average	64	57	37

[1] Average influent settleable solids for the three runs: 0.5 gpm - 0.22 percent; 0.75 gpm - 0.18 percent; 1.2 gpm - 0.19 percent.

[2] Average upper effluent settleable solids concentrations for two of the runs: 0.5 gpm - 0.67 percent, and 0.75 gpm - 0.20 percent.

[3] Rotational speed: 2 rpm.

not receiving a representative sample of manure solids, and (c) the solids-rich fraction discharged at the upper end contained too much water, yielding a solids fraction with too low a concentration.

MODIFICATION AND EVALUATION

To increase the solids concentration in the thickened upper effluent, certain alterations of the fins were deemed necessary. This change consisted of drilling a series of 1/4-inch holes at an angle of 6 degrees to the tube walls in the upper four fins of the separator. The 6-degree angle was chosen because testing to that time had been done with the tube set at a 7-degree angle to the horizontal. Therefore, when the tube was in testing position, the angle of the holes through the upper four fins was one degree (down slope) from the horizontal. These holes drained off part of the volume of water trapped by the upper four fins, making the concentration of solids higher in the upper effluent. A schematic diagram of the modified tube is shown in Figure 7.

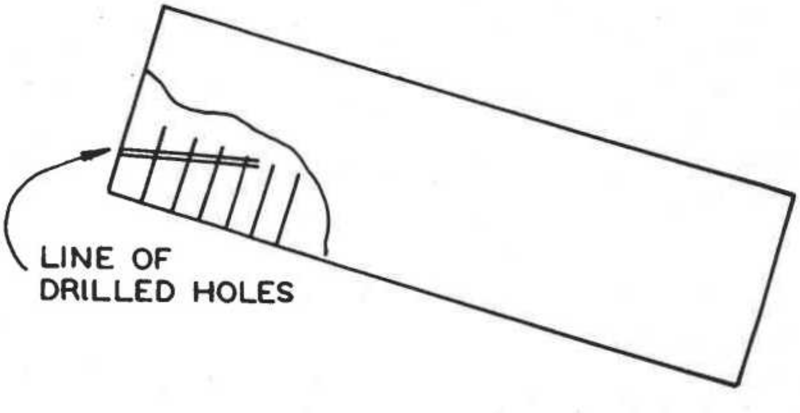

Figure 7. Schematic diagram of the 8-inch RFC tube modified by drilling a series of 1/4-inch holes in the upper wraps of the fin.

Two additional tests were made with beet pulp to see what effect this alteration might have on separation efficiency and upper effluent solids concentration. These runs were made at 0.5 gpm. Data for these two runs are shown in Table 2. A definite improvement in the upper effluent suspended concentration was obtained by the modification without a sacrifice in solids removal efficiency.

REVISED DESIGN

After observing the initial separator performance, a second generation device has been designed and fabricated. The major changes have been an increase in shell diameter to 24 inches and an increase of basic flight depth to 6 inches. Flights are on a 4-inch spacing. To decrease the amount of water carried out the upper end with the solids, the upper six flights have been decreased in height in a stepwise fashion as shown in Figures 8 and 9. Physical characteristics of the first and second experimental tubes are compared in Table 3.

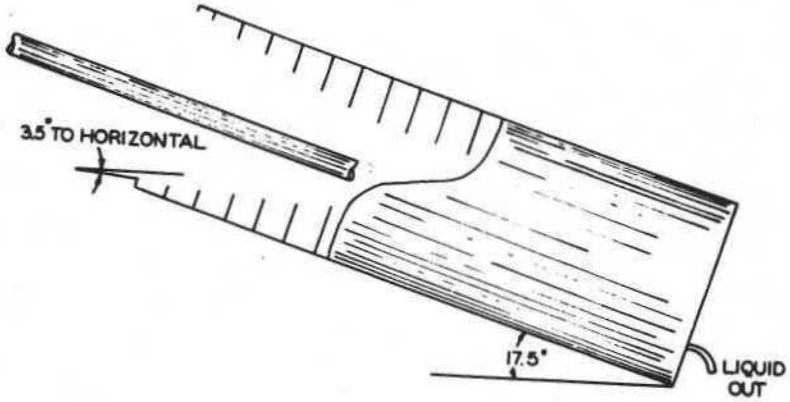

Figure 8. Sketch of the 24-inch diameter RFC solid-liquid separator tube.

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Table 2. Percent settleable solids removal and upper effluent settleable solids concentration for the modified separator receiving a beet pulp slurry.

Time, min	Influent settleable solids, %	Settleable solids removal, %	Settleable solids concentration of upper effluent, %
		Run A (average 62%)	
10	0.35	57	--
20	0.34	54	--
35	0.35	69	0.15
50	0.30	75	--
70	0.30	65	--
90	0.27	61	0.13
120	0.24	49	--
150	0.24	54	0.72
180	0.25	72	1.60
		Run B (average 59%)	
10	0.39	59	--
20	0.39	64	--
35	0.37	65	0.11
50	0.36	60	--
70	0.31	61	--
90	0.29	63	0.43
120	0.26	55	--
150	0.24	53	--
180	0.21	46	0.82
210	0.21	59	1.43

Table 3. Physical parameters of the 8-inch and 24-inch diameter tubes for solid-liquid separation.

Parameters	8-inch	24-inch
Tube diameter, inches	8	24
Tube length, inches	57	60
Fin height, inches	2	6
Fin spacing, inches	2.25	4
Mounting angle to horizontal, degrees	7	17.5
Volume of water between fins:		
cubic inches	22	355
gallons	0.095	1.54

Notes:
1. Upper five rounds of the fin in the 24-inch diameter tube have heights of 1, 2, 3, 4, and 5 inches, respectively.
2. The peripheral speeds are the same for both the 8-inch and 24-inch diameter tubes.

TWENTY-FOUR INCH TUBE

Two needs encountered immediately in evaluating the device for removing solids from dairy manure slurry were: (a) a slurry-feeding system, and (b) a sampling technique which adequately reflected its performance. An air-lift pumping system was devised which had the capability of providing flow rates of 2 to 60 l/min from a barrel continuously receiving and discharging a high flow rate of a well-agitated manure slurry. An alternative that also proved satisfactory was a gasoline engine driven variable speed diaphragm pump. The sampling problem was resolved by the fabrication of a funnel strainer as shown in Figure 10, which was used to collect the flow for a specified time. The volume collected

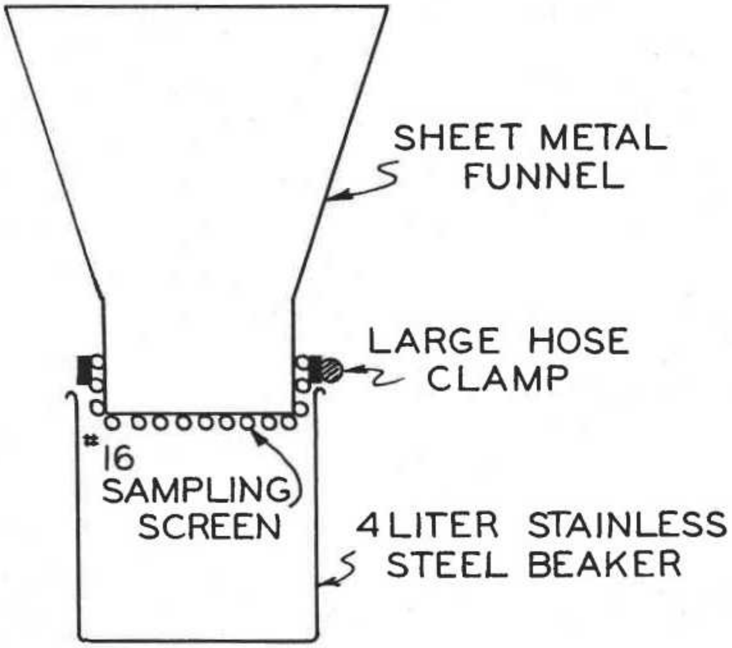

Figure 10. Cross section of the funnel-strainer used to evaluate the performance of the 24-inch diameter RFC used to remove solids from dairy and swine manure slurries.

was measured, the solids retained on the screen (1.19 mm openings) weighed, and the moisture content determined. From these data it was possible to calculate the retained solids content of the influent and two effluent streams.

When a dilute (0.05 to 1.2 percent retained solids) dairy manure slurry from flushing a free stall dairy barn was passed through the rotating cylinder, retained solids removals ranged from 20 to 80 percent, depending primarily upon the flow rate. These data are summarized in Table 4. Most of the discharged solids greater than 1.19 mm were wood chips, plant stems, and other low density materials not subject to removal by sedimentation. During the testing of this device, power consumption was measured and found to be 0.136 hp, independent of flow rate. This power consumption does not include lifting the slurry from the storage reservoir to the separator.

Table 4. Summary of performance data from tests of the 24-inch diameter rotating flighted cylinder with dilute dairy manure slurries.

Flow rate range, 1/min	Average retained solids removal, %[1]	Average concentration factor[2]
4 - 12	54.1	11.7
12 - 16	46.4	12.3
16 - 20	34.6	13.9
20 - 24	28.6	14.0
24 - 28	10.5	7.5
28 - 36	14.3	10.2
36 - 50	13.1	12.5

[1] Retained solids are defined as those which will not pass through a screen with 1.19 mm openings.

[2] Concentration factor is the upper retained solids concentration divided by the influent retained solids concentration.

Utilizing the same separator and air-lift pump as previously described, a series of trials were conducted to determine the performance of the unit in removing solids from a dilute swine manure slurry. A gasoline-powered diaphragm pump lifted the slurry from a pit beneath a partially-slatted feeding floor to the barrel holding the air-lift pump. The swine were fed a finely ground complete ration pelleted for storage and handling ease. There was no floating material present in the slurry. Flow rates to the separator ranged from 17.8 to 26.5 1/min. In every trial, the device removed all solids retained by a screen with 1.19 mm openings. Concentration factors as defined in Table 4 ranged from 20 to 112, with a median of 62. Solids-stream retained solids were as high as 4.3 percent when the feed slurry was 0.04 percent retained solids.

BIOLOGICAL WASTE TREATMENT CONSIDERATIONS

Biological waste treatment systems in which a solid surface is alternately exposed to the atmosphere and to a soluble BOD-laden water are commonplace in wastewater treatment technology. Trickling filters, contact beds, and sand filters represent prime examples. Rotating disk processes, which function similarly for the removal of soluble BOD, have been applied to municipal sewage (Autotrol Corporation, 1971) and to partially treated livestock wastes (Miner et al., 1973). In the rotating disk process, parallel circular disks mounted on a horizontal shaft are slowly rotated, one to five revolutions per minute. The shaft is mounted just above the water surface of a tank so the disk surfaces are alternately exposed to the atmosphere and submerged in the wastewater. A biological growth, similar to that on trickling filter stones, develops on the disk and feeds upon the dissolved waste materials. As the growth becomes sufficiently heavy, portions are shed, which can be removed from the water by traditional sedimentation processes. BOD removals of up to 90 percent were reported by Autotrol Corporation (1971) for a pilot plant treating municipal sewage. The major advantages of this process over activated sludge are lower power consumption and less complex mechanical equipment.

The rotating flighted cylinder is envisioned as having the potential to operate in a manner biologically similar to a rotating disk system, with the additional advantage that a separate sedimentation device would not be required. Solids sloughed from the fin would be worked upward in the tube and returned to the wet-well from which the waste was pumped. Since the device also has solid-liquid separation capabilities, the traditional functions of primary and secondary wastewater treatment might be accomplished in a single unit. If successful, this device would have application in the treatment of domestic wastes from small systems as well as livestock wastes.

OXYGEN TRANSFER

Aeration theory suggests that the magnitude of oxygen transfer in an RFC unit is a result of the degree of surface renewal, or turbulence. A rigorous quantitative model describing re-aeration would be complex because of the hydraulic characteristics which include, in effect, a stream flowing down the cylinder running transverse to the augered stream. It would appear more productive to rely on empirical data in developing a relationship between measurable parameters and aeration rates. Power consumption for various wastewater aerators reported by Hervol and Pyle (1973) is given in Table 5.

Table 5. Oxygen transferred per unit power consumed.

Aerator	Kg O_2/kw - hr
Submerged turbine with sparger	1.6
Diffused aeration	2.7
Slow-speed turbines	3.7
High shear axial flow	2.2

ORGANICS REMOVAL

A biological growth medium intermittently exposing its microbial population to a liquid and gas phase has been described as a two-phase contact (TPC) system (Welch, 1968). The predominant form of TPC treatment is the rotating biological disk (RBD) unit which has biological characteristics closely paralleling the RFC. This type of operation incorporates characteristics of the trickling filter and activated sludge processes into one unit by providing a media for fixed growth and a mechanism for continuous aeration.

Two-phase contact was first investigated in the United States by Buswell in 1929 on a unit he referred to as a biological wheel. Buswell's report concluded that the actual area occupied by the unit was about one-tenth of that required for a trickling filter, power cost was low, and nitrification was accomplished (Canale, 1971). An experimental unit was later developed and A. T. Maltby secured a patent for it in 1931. TPC systems have been used for wastewater treatment for over 15 years in Europe (Antonie et al., 1974) and by 1969, more than 400 such operations existed there.

Perhaps one of the most important characteristics of the TPC system is its ability to maintain a very high microbial population during operation. Joost (1969) found food-to-microorganism ratios to be .02-.05 in an RBD system, whereas activated sludge values are typically .03. Equivalent mixed liquor volatile suspended solids (MLVSS) concentrations have been found at 17,000 mg/l and 50,000 mg/l as compared to activated sludge values of around 3,000 mg/l (Welch, 1969). The large number of organisms expedites the stable treatment of concentrated waste and shock loadings. This attribute has made TPC systems attractive to industrial, as well as municipal, waste treatment.

Movement of the supporting media provides turbulence which enhances treatment efficiencies by increasing aeration of wastewater and promoting biological activity. The latter phenomenon was described by Hartmann (1967), who showed that biological activity was increased by the transport of substrate and oxygen to a fixed biofilm by turbulence. Oxygen transfer is further expedited by exposure to the gas phase where the thin layer of waste covering the film is aerated under conditions providing a constant and excess supply of oxygen. While the rate-limiting step in trickling filter biofilms is most often oxygen transfer, two-phase contact provides a means for minimizing this effect.

In a rotating disk unit study, Pretorius (1971) noted that the quantity of growth varied significantly throughout a series of disks with the growth thicker in the influent section. In addition, he observed a distinct difference in the nature of the microbial population on the different disks, evidently due to the plug-flow regime in the unit.

The amount of biomass supported by the medium is limited by shearing forces, inability of biomass to support its own weight, possible anaerobic conditions at the surface of the medium, and concentration of substrate (Welch, 1969). Pretorius (1971) obtained a maximum biomass of 43 gm/m^2 dry weight. Borchardt found biomass growth at approximately 200 gm/m^2 dry weight (Canale, 1971).

Several investigators have demonstrated that RBD processes are capable of achieving high degrees of nitrification. Antonie _et al._ (1974) has shown that when the wastewater BOD concentration approaches 30 mg/l, nitrifying organisms can compete with the more rapidly growing carbon oxidizing organism. Nitrification then proceeds rapidly and is virtually complete when BOD concentration is approximately 10 mg/l.

Actual operation of two-phase contact systems has yielded treatment efficiencies of 80 to 90 percent when combined with primary and secondary clarification (Antonie _et al._, 1974). The following observations have been made during operation of RBD systems and presumably resulted from characteristics also inherent in the rotating flighted cylinder.

1. Concentrated wastes can be effectively treated.
2. Shock load capabilities are excellent.
3. Bulking, foaming, or floating sludges are never a problem.

4. Washout potential is non-existent.
5. No clogging problems are evidenced as in trickling filters.
6. Volume of sludge produced is low and it dewaters more readily than waste-activated sludge.
7. There is nitrification at low organic loadings.
8. Effluent has a slightly brownish color, typical of biological filters.
9. Operation is simple and maintenance low.
10. Power requirements are low.

WASTEWATER TREATMENT COSTS

Marginal costs for increased capacity in wastewater treatment are sufficiently small so as to create substantial decreases in cost per unit volume treated. Unfortunately treatment plants the size common to package plants present unit costs quite in excess of larger facilities. Nicoll (1971) found costs for extended aeration package plants in Great Britain to be as shown in Figure 11. The Federal Water Pollution Control Administration (FWPCA, 1968) reported the cost indicated by Figure 12 for similar plants in the United States. In a study of package treatment plant prices, Lamp (1974) tabulated the prices shown in Table 6.

Table 6. Mean list price of package plants by plant size (Lamp, 1974).

Plant size, gpd	# of plants in samples	Mean list price, $	Standard deviation
300	4	877	301
500	7	1,593	765
600	6	1,031	379
900	3	1,358	221
1,000	9	2,572	2,537
1,500	9	2,526	822
2,000	7	5,017	2,182
2,500	4	4,530	1,672
3,000	5	6,605	2,384
4,000	6	7,088	2,170
5,000	11	8,690	2,133

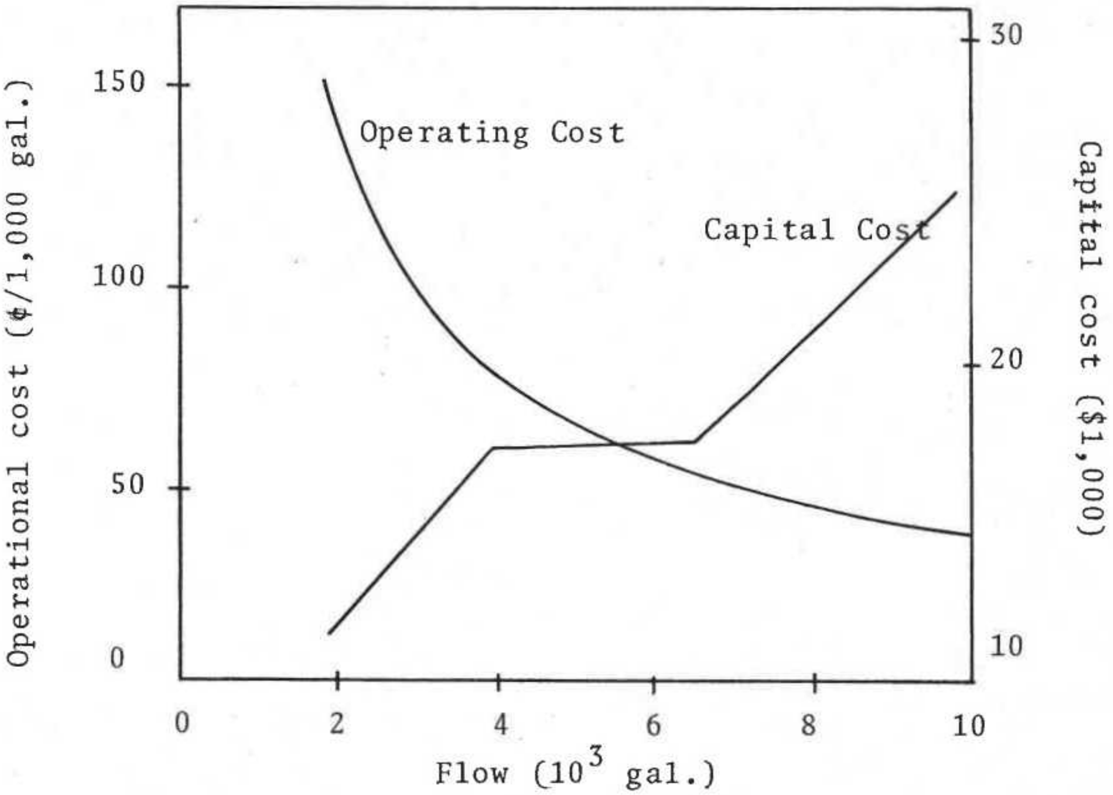

Figure 11. Operating and capital costs of package treatment plants according to Nicoll (1971).

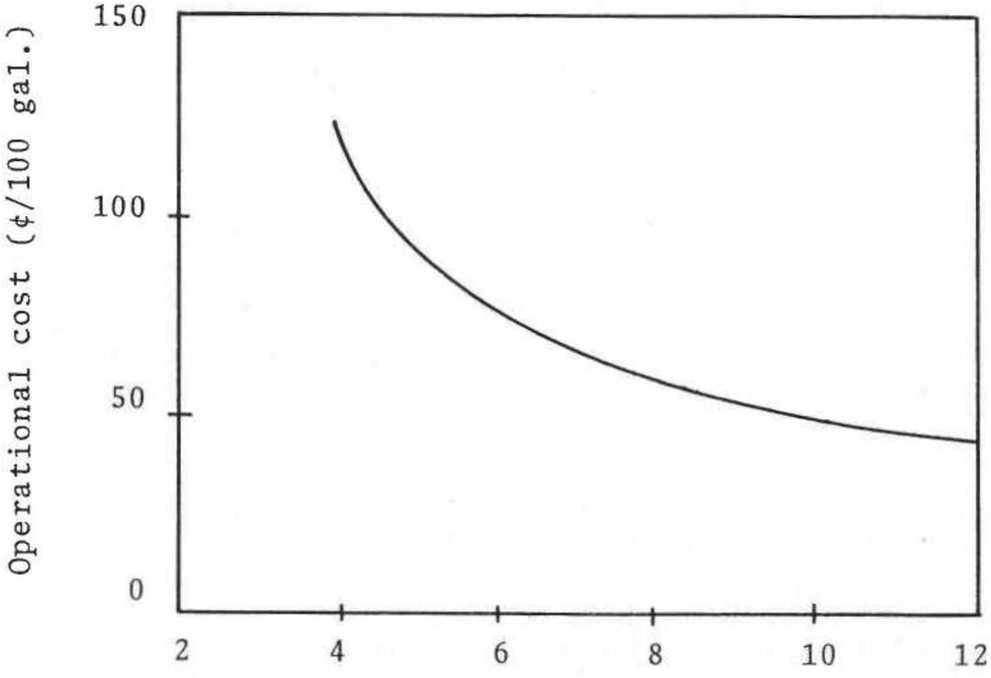

Figure 12. Operating and capital cost of package treatment plants according to FWPCA (1968).

EVALUATION OF THE RFC FOR BIOLOGICAL WASTE TREATMENT

RFC units were set up and operated at the Water Research Demonstration Laboratory of Oregon State University adjacent to the Corvallis Wastewater Treatment Plant for domestic sewage studies. Two RFC units of 8- and 24-inch diameters were investigated. Table 3 gives the physical dimensions and Figure 13 shows the 8-inch unit.

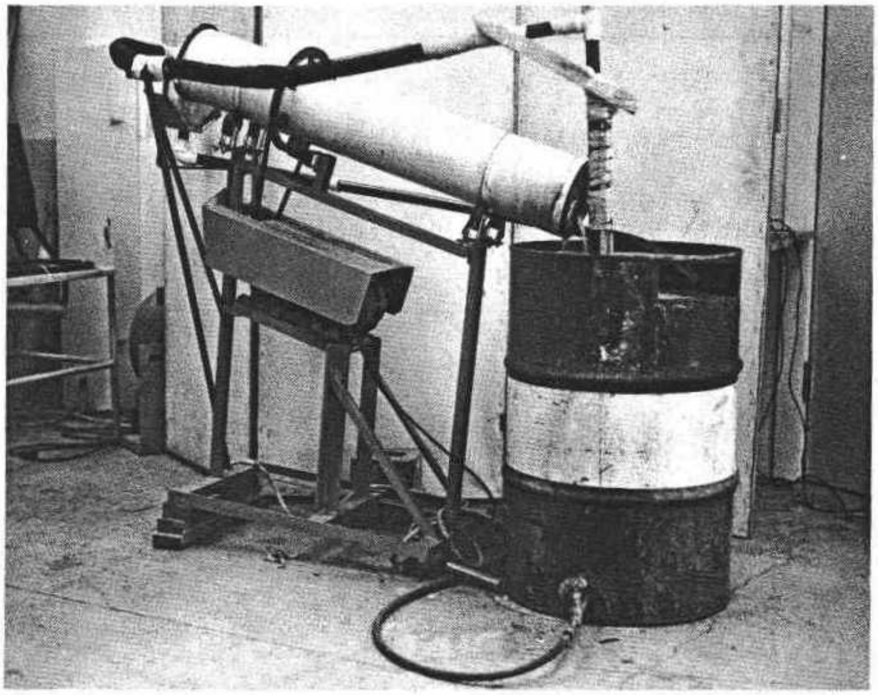

Figure 13. Eight-inch diameter RFC unit in operating position.

For sewage treatment, comminuted raw sewage was pumped from the treatment plant to the laboratory where it was made available for the RFC system. The 8-inch RFC was initially set up with a 55-gallon metal barrel into which cylinder effluent emptied and from which cylinder influent was pumped by an air-lift pump. This system was fed by delivering a slug load of the desired volume of waste to the barrel. For the continuous flow regime of both RFC's and the batch treatment of the 24-inch RFC, the system tested consisted of two 55-gallon metal barrels connected by a 2-inch steel pipe located one inch from the bottom of each barrel (Figure 14). A submerged centrifugal pump at the bottom of the influent barrel pumped sewage through a one-half inch tygon tube to the upper end of the cylinder. Flow rate was controlled by pinching the tubing. Fluid flowed through the inclined cylinder as it rotated such that a portion of the flow exitted through the lower end of the cylinder into the effluent barrel while the remaining flow was augered back to the upper end, where it was returned to the influent barrel. Because of the low flow rates required for continuous flow treatment, influent sewage from the plant line was run into an overflow reservoir from which a low flow rate pump delivered it to the RFC system. An air-lift pump was employed to accomplish this during operation of the 8-inch cylinder, but due to difficulty in monitoring and regulating flow rates, a variable speed Masterflex tubing pump was used during operation of the 24-inch cylinder. Effluent from the entire system left the effluent barrel at an opening cut 4 inches below the top of the barrel.

For oxygen transfer determinations, a plug was inserted in the 2-inch pipe connecting barrels so that only the effluent barrel was used. The centrifugal pump was placed at the bottom of this barrel and delivered water to the cylinder's upper end. Augered effluent was returned to the effluent barrel. The sodium sulfite/cobaltous chloride method (Eckenfelder and O'Connor, 1961) was used to deoxygenate tap water. A Yellow Spring Instruments Dissolved Oxygen Meter/Model 54 was used to measure oxygen concentrations. For the 8-inch cy-

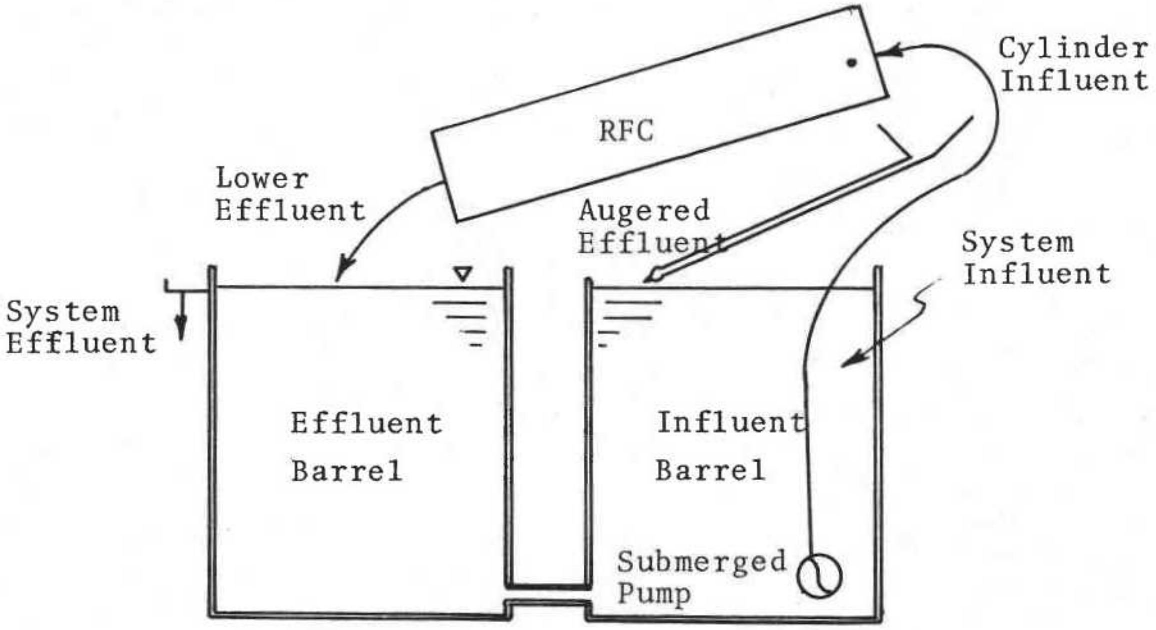

Figure 14. RFC system for batch and continuous flow treatment.

linder, 14 grams of Na_2SO_3 and a pinch of CoCl were added to the barrel of tap water, stirred, and allowed to stand several minutes. Flow and rotation were then started and dissolved oxygen in the barrel was recorded at 5-minute intervals until the dissolved oxygen concentration reached 7 mg/1.

The 24-inch cylinder was deoxygenated somewhat differently because the cylinder held a significant volume of water. After filling the barrel with tap water, 14 grams of Na_2SO_3 and a pinch of CoCl were added. One-hundred liters were then pumped into the cylinder without rotation and an equal amount of tap water was added to the barrel to fill it again. More Na_2SO_3 (7.5 grams) was added to the barrel, stirred, and allowed to stand several minutes. Flow and rotation were then started and dissolved oxygen concentration was recorded at 2-minute intervals. All dissolved oxygen tests were run at temperatures between 15 and 20° C.

OPERATING EXPERIENCE

In principle, operational and maintenance care of an RFC unit is minimal and simple. However, during this investigation, engineering problems arose requiring special attention. Other than maintaining dependable flow rates with the air-lift pump, operation of the 8-inch RFC proceeded smoothly.

The 24-inch RFC presented unanticipated problems primarily due to its weight. Shortly after commencing operation, the belt from the drive shaft to the cylinder was unable to maintain sufficient friction and slipping became frequent. This situation was remedied by increasing tension on the belt. Although this solved the immediate problem, it created excessive wear on the shaft bearings and caused increased power consumption. More sophisticated engineering of the mechanical aspects of the system could no doubt alleviate this problem.

A second unexpected difficulty arose when the 24-inch RFC failed structurally. Abrasive wear and flexural stresses produced a crack where the lower rollers contacted the cylinder. By doubling the number of lower rollers from two to four and thickening the contact area with a fiberglass band approximately one-quarter inch thick and 8 inches wide, the load was sufficiently spread to relieve the problem. Shortly before termination of data collection, the contact area of the upper rollers developed a similar failure which was temporarily repaired by a small epoxy-fiberglass band. Occasional pump clogging plagued the system but better-adapted pumps could eradicate such occurrences. No operational problems were encountered that appeared inherent in the RFC process. The entire system could be designed so as to require practically no operational or maintenance attention.

The time required to achieve a full microbial growth in the 8-inch RFC was one week. The 24-inch RFC was initially operated for three weeks before it attained a full growth; this appeared to be due to the smooth, slick surface which created problems of adherence. Once growth appeared (after the second week), it proceeded rapidly and later start-ups after growth had dried out completely required about a week to reach full density. Growth was considered "full" when the interior surface was completely covered with a thick bacterial slime.

Results of solid-liquid separation measurements in the 8-inch cylinder indicates that suspended solids are removed in the unit but that the mechanism appears to be by dissolution rather than by sedimentation. For a range of flow rates, both the lower and augered effluents often had a lower suspended solids concentration than the cylinder influent (Table 7).

Solid-liquid separation, as well as liquefaction, was accomplished by the 24-inch RFC as Table 8 illustrates. The augered effluent was visually noted to contain large amounts of sloughed biomass in every case whereas sloughed biomass was seen only at the highest cylinder flow rate in the lower effluent. Solids removal increased with rotational speed. Solids concentration in the augered effluent decreased with rotational speed, as expected.

The effect of rotational speed on augered effluent concentration is influenced by two factors, turbulence and flow rate. As rotational speed increases, turbulence within the helical channel creates conditions less conducive to efficient settling and more expeditious to the dissolution of soluble particles by physically breaking them up, thus exposing more surface area, proving a greater rate of liquid turnover at the solid-liquid interface of the particles.

Table 7. Results of solid-liquid separation tests with the 8-inch RFC treating domestic sewage.

Cylinder influent, lpm	Suspended solids, mg/l		
	Cylinder influent	Lower effluent	Augered effluent
2.3	161	167	162
2.8	184	186	153
4.1	195	186	181
4.6	94	85	73
6.9	211	164	174
10.4	102	---	87

Table 8. Results of solid-liquid separation tests with the 24-inch RFC treating domestic sewage.

Cylinder influent, lpm	Augered effluent, lpm	Rpm	Suspended solids, mg/l		
			Cylinder influent	Lower effluent	Augered effluent
7.5	4.4	2.00	176	133	204
6.8	3.0	1.36	201	161	184
7.7	1.8	0.82	99	92	98
21.1*	2.9	1.36	193	194	168
7.8*	5.0	2.31	141	72	157
8.8*	3.1	1.36	130	81	152
7.6	2.1	0.94	104	75	179

* Raw sewage introduced with recirculated flow directly into cylinder.

Flow of augered effluent increases proportionally with rotational speed; therefore, the rate of solids accumulation would have to increase with flow in order to maintain a constant solids removal on concentration. But due to turbulence, solids accumulation is actually less and the dilution effect of the increased flow further limits solid-liquid separation. The sloughing of biomass might be increased by the higher shear of larger flows but the rate of sloughing is probably less than proportional to flow rate since the ability of the biomass to support itself is a function of other things in addition to shearing forces.

An important characteristic of the RFC, in contrast to trickling filter and RBD processes, is its ability to remove the solids it produces. While all three operations depend on the mechanism of converting substrate BOD to biomass for a significant portion of their BOD removal capacity, the RFC alone has the potential of eliminating secondary clarification.

OXYGEN TRANSFER STUDIES

Data obtained from aeration tests indicate that oxygen transfer is enhanced by increasing flow rate and rotational speed. It was also observed that the difference in oxygen concentration between lower effluent and augered effluent was a function of flow rate and rotational speed. At high rotational speeds (2.5 rpm), lower effluent showed higher dissolved oxygen concentration than augered effluent, while at lower speeds (0.95 rpm), the reverse was true. As the flow rate increased, the difference became less (Figure 15).

The re-aeration rate of the augered stream is thought to be influenced by turbulence and by the rate at which a thin liquid layer is exposed to the air phase, although the relative contribution of each cannot be ascertained. Increasing rotational

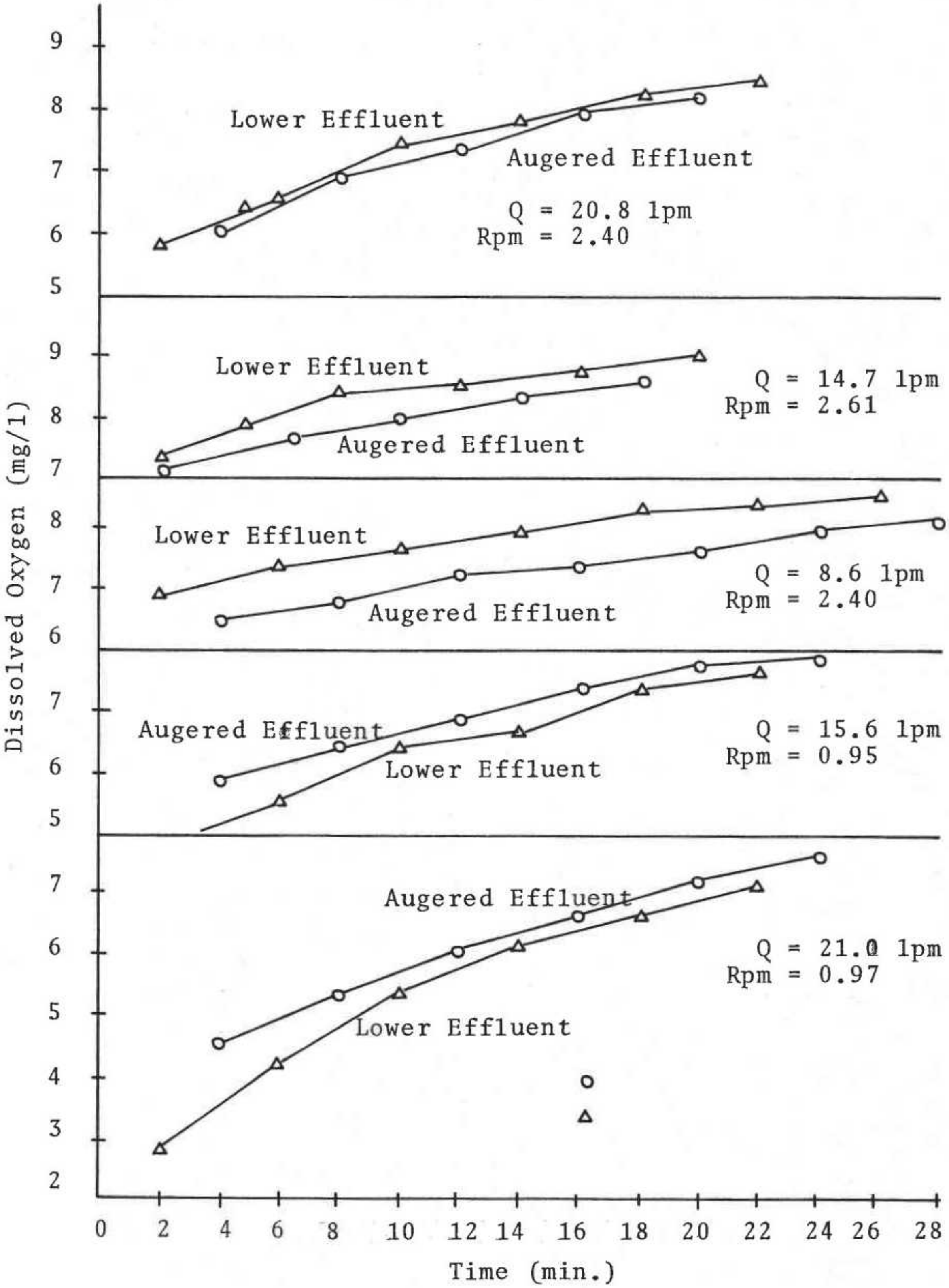

Figure 15. Dissolved oxygen concentration of augered and lower effluents in the 24-inch RFC during aeration studies.

speed will cause both mechanisms to increase oxygen transfer. If the rate of total oxygen transferred is less than proportional to rotational speed, then augered effluent will have lower dissolved oxygen concentrations at higher rpm's since augered flow is proportional to rotational speed. Also, residence time in the cylinder contributes significantly to the rise in oxygen concentration. These effects probably account for the positions of the dissolved oxygen lines in Figure 15. Decreases in the differences between these lines are attributed to increased turbulence and corresponding mixing at higher flow rates. A Reynold's Number based on the flow over a circular weir is shown in Figure 16 (Mavis, 1949).

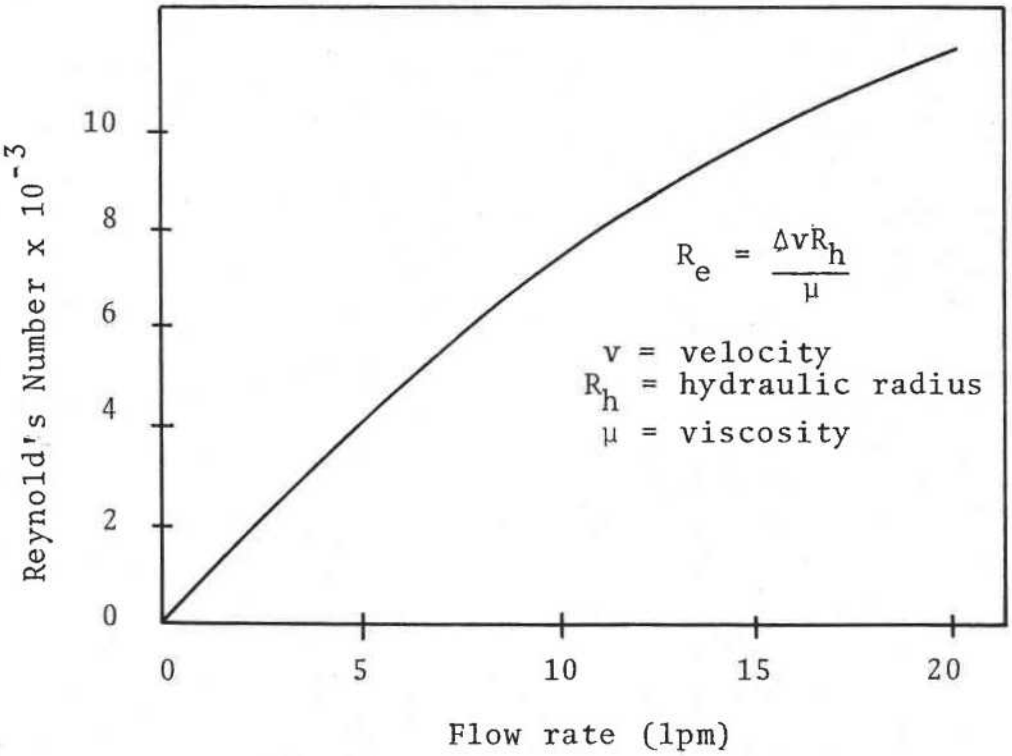

Figure 16. Reynold's Number for flow over a circular weir in the 24-inch RFC.

Efforts to develop a definite correlation between re-aeration data and a turbulence parameter proved futile. While it appears obvious (Tables 9 and 10) that increased flow and rotation (both of which caused increased re-aeration rates) contribute to greater agitation and mixing, no adequate parameter based on flow, geometry and/or rotational speed was developed. Figures 17 and 18 show empirical relationships for the 24-inch RFC unit. Figure 18 indicates that there is a maximum flow corresponding to a given rotational speed where oxygen transfer is no longer enhanced by increasing flow rate. This leveling-off effect is probably due to increased depth in the stream flow, which, according to stream aeration theories (Dobbins and O'Connor, 1958), would actually lower the rate of re-aeration within the stream itself. Increased flow would tend to cancel the decreased concentration rate, thus creating a more or less constant overall rate coefficient.

Table 9. Re-aeration coefficients and oxygen transfer capacity for the 8-inch RFC.

Cylinder, lpm	k_La, hr^{-1}	Oxygen transfer, gm/day
2.1	0.483	20.9
2.6	0.566	24.5
2.8	0.508	21.9
3.0*	0.565	24.4
3.0	0.583	25.2
4.6	0.593	25.6
12.5	2.120	91.6

* No rotation.

Table 10. Re-aeration coefficients and oxygen transfer capacity for the 24-inch RFC.

Cylinder influent, lpm	Rpm	$k_L a$, hr^{-1}	Oxygen transfer, gm/day
4.3	0.00	0.47	30.3
6.0	0.00	0.74	47.9
8.6	2.40	1.89	122.5
11.7	0.00	1.89	122.5
11.6	0.72	1.72	111.5
11.6	0.89	1.84	119.2
11.2	1.76	2.24	145.2
11.3	2.55	2.32	150.3
11.8	2.50*	2.96	191.8
11.8	2.66	1.92	124.4
15.0	0.00	1.93	118.6
15.2	0.73	2.57	166.5
15.2	0.94	2.50	162.0
15.6	0.95	2.38	154.2
14.8	1.36	2.88	186.6
15.3	2.55	3.06	198.3
14.7	2.61	3.17	205.4
19.7	0.00	1.86	120.5
21.0	0.97	2.54	164.6
20.8	2.40	3.95	256.0

[*] Opposite rotation.

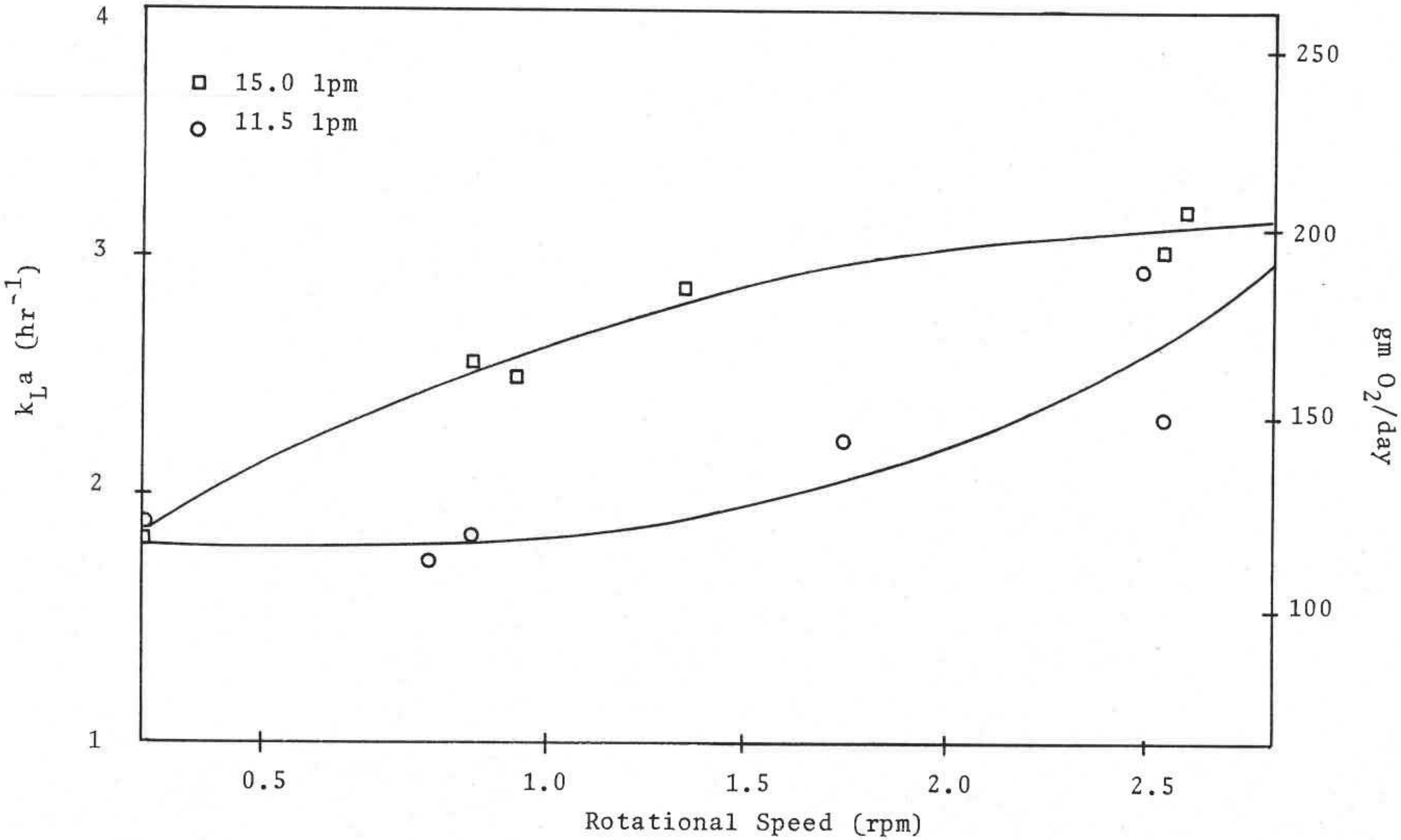

Figure 17. Oxygen transfer rate vs rotational speed in the 24-inch RFC.

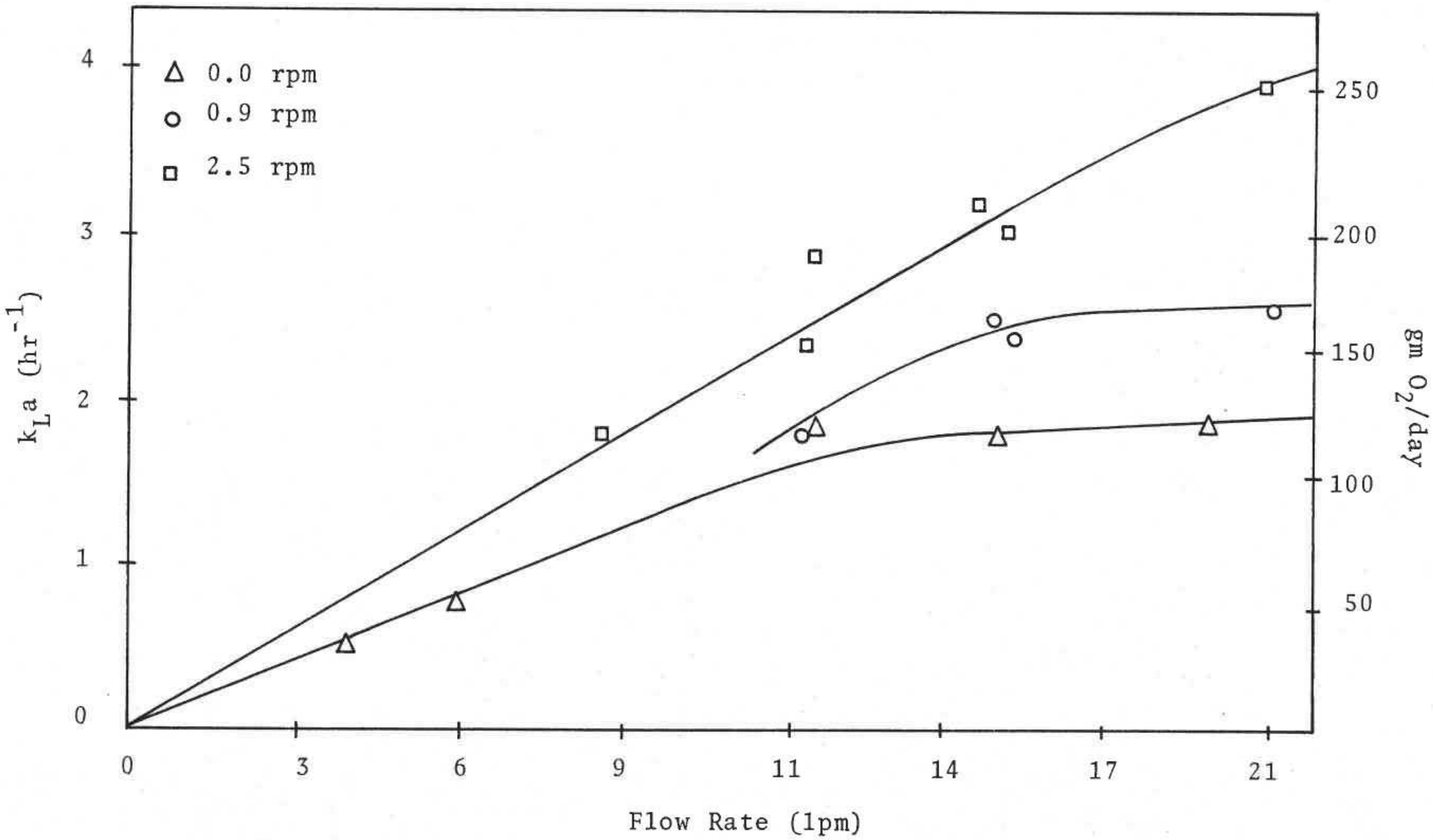

Figure 18. Oxygen transfer rate vs flow rate in the 24-inch RFC.

A comparison of BOD removal and re-aeration capacity indicates that BOD is removed two to three times faster than oxygen is being supplied when $BOD_{ult} = 1.5 \times BOD_5$. Two reasons for the existence of this situation are listed below:

1. Removal of BOD through sedimentation.
2. Aeration of the thin layer of waste on the biofilm as it is exposed to the air phase contributes significantly to re-aeration in a manner not fully reflected by the re-aeration test.

Power consumption in the RFC system resulted from an influent pump, a recycle pump, and a motor rotating the cylinder. Since the need for an influent pump will depend on whether or not the treatment site allows for gravity flow, this source of power consumption is not included in the usage of the RFC system.

Figure 19 shows power consumption for the recycle pump based on flow through a 10-foot, one half-inch steel pipe and an elevation head of 2.5 feet. Figure 20 shows power consumption for a one-half horsepower motor rotating the cylinder. The motor values were obtained from actual wattage readings during operation of the system and it is conceivable that more refined engineering could reduce the amount of energy required here.

As an aerator the RFC unit tested is far less efficient than conventional aeration units (Table 5). Using re-aeration test data, the 24-inch RFC has an oxygen transfer efficiency of about 40 grams O_2/kw-hr. By calculating an efficiency based on the soluble BOD removed, the transfer becomes significantly larger. Batch tests showed that as much as 150 mg/l of soluble BOD could be removed in a two-hour detention per-

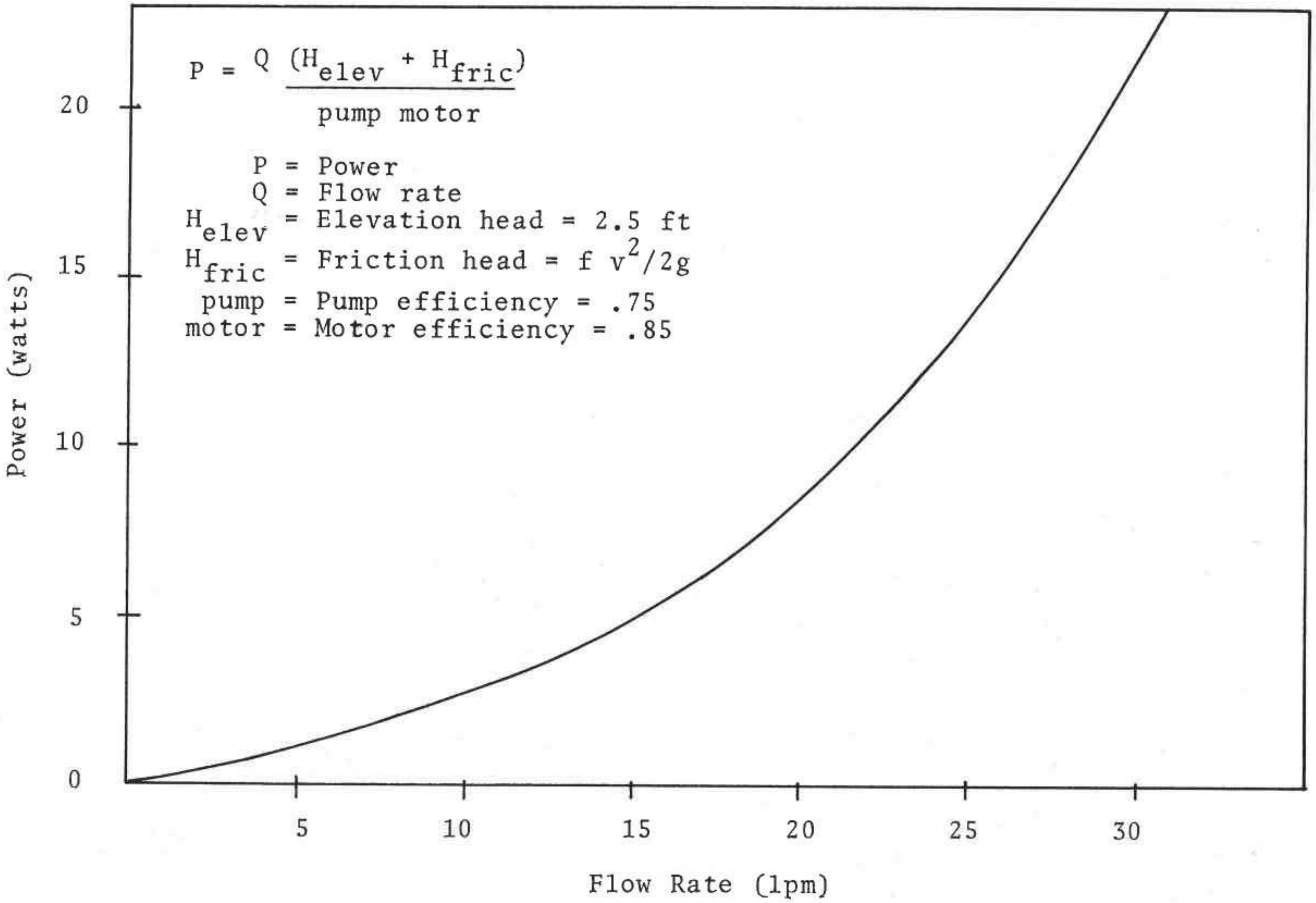

Figure 19. Pump power consumption in RFC system.

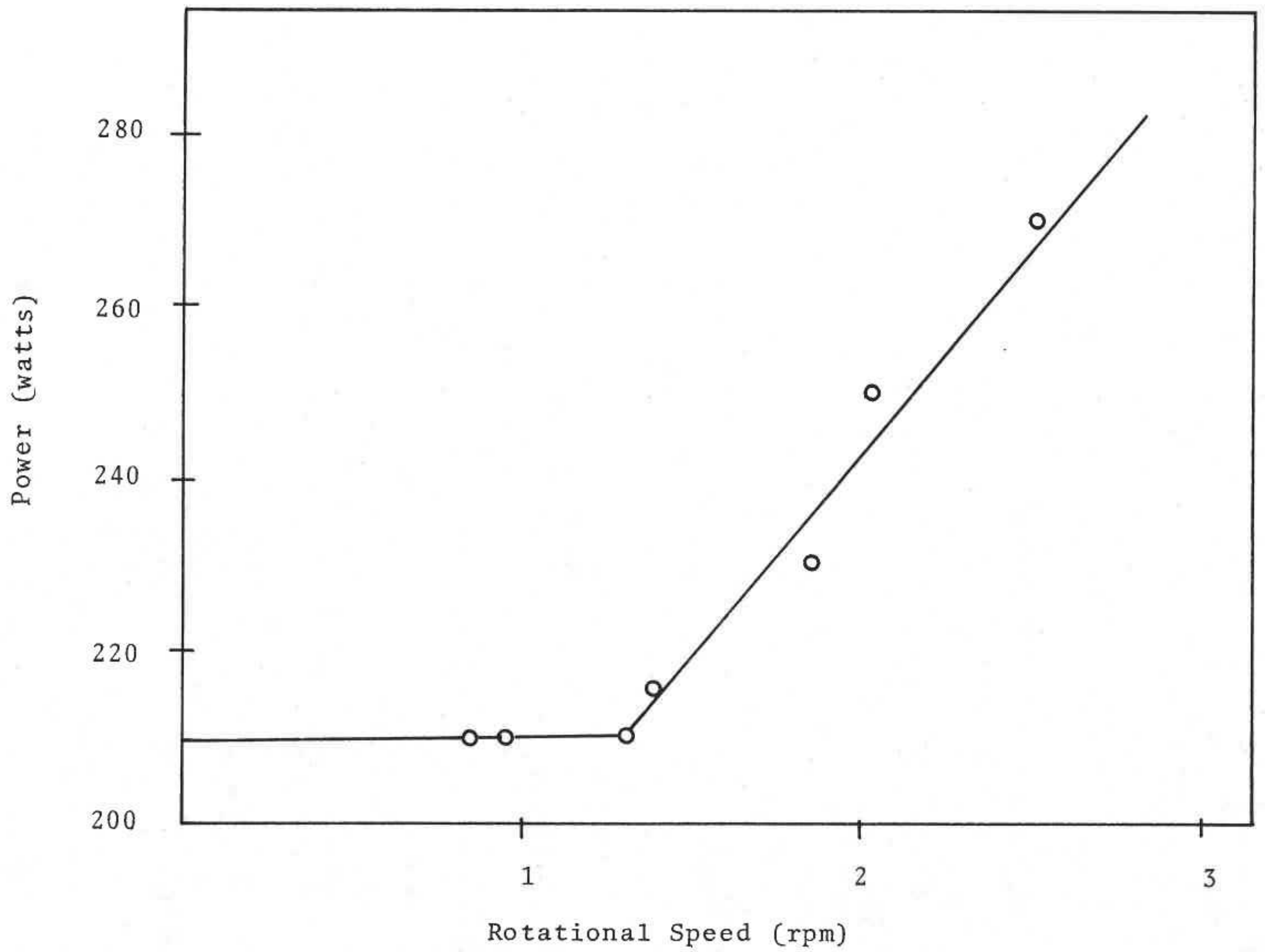

Figure 20. Power consumption of 1/2-horsepower motor used to rotate 24-inch RFC.

iod. By projecting BOD_{ult} to be 1.5 x BOD_5, the oxygen transfer efficiency is approximately 200 grams O_2/kw-hr. This value is probably conservative because of the inaccuracies inherent in the soluble BOD_5 measurements.

WASTE TREATMENT STUDIES

Evaluation of the biological treatment efficiency of the RFC was somewhat obscured by accumulation of solids in the influent and effluent barrels. By arranging the recirculating flow so that liquid was pumped from the bottom of the barrels, it was hoped to keep solids sufficiently dispersed throughout the system so as to avoid their deposition (Figure 14). In spite of this, sedimentation in the barrels appeared to account for removal of a portion of the waste load.

Two different feed systems were used to test the treatment capabilities of the 8-inch RFC. A daily slug load of 120 liters of raw sewage was added to the single barrel system; results are given in Table 11. The second system (Figure 14) was a continuous flow regime with results given in Tables 12 and 13.

Table 11. Results of slug load fed system with 8-inch RFC. (Flow rate = 120 l/day; system volume = 200 l)

Day	Total BOD_5, mg/l			Total COD, mg/l		
	Inf.	Eff.	$k(hr^{-1})$	Inf.	Eff.	%
1	200	15	.0648	415	74	82
2	200	18	.0602	404	80	80
3	280	28	.0576	559	116	79
4	220	24	.0554	466	86	82
5	210	15	.0660	300	100	67
6	210	14	.0677	310	76	75
7	180	20	.0549	314	55	82

Table 12. BOD_5 results of municipal sewage continuous flow treatment with 8-inch RFC.

Influent flow, lpm	Cylinder influent, lpm	BOD_5 (total), mg/1				BOD_5 (soluble), mg/1			
		Inf.	Eff.	remov.	$k(hr^{-1})$	Inf.	Eff.	remov.	$k(hr^{-1})$
0.07	3.4	101	29	71.3%	.0131	23	10	56.5%	.0087
0.10	3.9	252	43	82.9%	.0265	93	23	75.3%	.0210
0.19	4.6	288	83	63.6%	.0355	78	21	73.1%	.0374
0.24	8.5	492	173	64.8%	.0376	235	80	66.0%	.0388
0.33	4.6	528	139	73.7%	.0661	199	24	87.9%	.1047
0.39	10.5	552	210	62.0%	.0565	237	109	54.2%	.0454
0.50	3.4	222	106	52.3%	.0554	90	35	61.1%	.0708
0.50	3.3	295	132	55.3%	.0603	118	52	55.9%	.0615
0.60	3.2	276	80	71.1%	.1115	66	21	68.2%	.1031
0.71	3.4	336	104	69.1%	.1249	116	39	66.4%	.1161
0.90	2.7	187	84	55.1%	.1080	76	38	50.0%	.0936
1.68	2.7	282	180	36.2%	.1131	114	92	19.3%	.0540

Table 13. COD results of municipal sewage continuous flow treatment with 8-inch RFC.

Influent flow rate, lpm	Cylinder flow rate, lpm	COD (total), mg/l			COD (soluble), mg/l		
		Inf.	Eff.	Removal	Inf.	Eff.	Removal
0.07	3.4	380	121	68.2%	105	75	28.6%
0.10	3.9	454	133	70.1%	163	72	55.8%
0.19	4.6	451	172	61.9%	174	91	47.7%
0.24	8.5	900	327	63.7%	524	192	63.4%
0.33	4.6	896	267	70.2%	485	88	81.8%
0.39	10.5	834	400	52.0%	472	230	51.3%
0.50	3.4	473	200	57.5%	184	81	56.0%
0.50	3.3	522	212	59.4%	207	110	46.9%
0.71	3.4	661	169	74.4%	176	73	58.5%
0.90	2.7	514	167	67.5%	159	125	21.4%
1.68	2.7	502	318	36.7%	175	147	16.0%

By considering the rate of BOD_5 removal to approximate a first order reaction, one can determine the rate constant for each system:

$$dL/dt = -kL$$

$$1/T \ln (L_{inf}/L_{eff}) = -k$$

where T is the average detention time in the system and L is BOD_5. For the seven runs of the slug load-fed system, an average k value of .0609/hr was obtained with a standard deviation of .00486.

The wide variation of influent concentrations presented difficulties in evaluating treatment efficiencies for the continuous flow system, and the unreliability of the influent air-lift pump accounted for a degree of inconsistency in the data. Nevertheless, average k values of .0674/hr for total BOD_5 and .0629/hr for soluble BOD_5 were calculated with standard deviations of .0379 and .0336, respectively.

Batch treatments with the 24-inch RFC indicated that the system was capable of high organic matter removal efficiencies but it was unclear as to what portion of treatment could be attributed to sedimentation and decomposition in the barrels. An attempt to ascertain the removal in the barrels was made by filling the barrels with raw sewage and allowing the sewage to remain without recirculation. Two separate non-circulating runs showed significantly different results but soluble BOD_5 and COD appeared to remain fairly constant. Since sedimentation in the barrels is minimized by the recirculation of the system, it is estimated that the cylinder is responsible for as much as 80 to 90 percent of the system's treatment efficiency.

Tables 14 and 15 show how treatment efficiency progressed with time. In determining rate coefficients, it was found that k values decreased with length of treatment. For total BOD_5 it is suspected that agitation and turbulence of the system enabled a greater BOD demand by the dissolution of particulates than was attained in the BOD bottle. This suggests that the system is actually removing more BOD than is reflected by the initial measurements. Soluble BOD_5 is affected by this same phenomenon but to an even greater extent. The difference between initial soluble BOD_5 and total particulate BOD_5 eventually solubilized in the system is greater than the difference between the particulate BOD_5 solubilized in the BOD bottle and that solubilized in the system. Since these relative amounts were unknown, the rate coefficients were calculated as an average of the measurements over a 12-hour period (Table 16).

The rate constants increased with increasing flow rates through the cylinder, probably due to greater re-aeration capacity at higher flow rates. Rate also appeared to be more rapid at high rpm's, probably again due to re-aeration and increased exposure to the air phase of the rotating biofilm.

The continuous flow run with the 24-inch RFC yielded lower treatment efficiencies than equivalent batch treatments, except for removal of soluble BOD_5 (Table 17). When the average continuous flow detention time is compared to a similar batch treatment detention time, it is seen that total COD removal is about 12 percent lower, soluble COD is about 6 percent lower, total BOD_5 is 15 percent lower, and soluble BOD_5 is approximately the same. The higher suspended solids concentration in the effluent appeared responsible for the lower efficiencies of the "total" measurements. This was also reflected in the rate constant for total BOD_5 removal. The soluble BOD_5 rate constant is about the same as the batch treatments when variation with cylinder flow is considered.

Table 14. BOD_5 and DO results of municipal sewage batch treatment with 24-inch RFC.

Detention time, hr	Cylinder flow, lpm	Rotating speed, rpm	Total BOD_5, mg/1				Soluble BOD_5, mg/1				DO, mg/1
			Inf.	Eff.	Remov.	k(hr^{-1})	Inf.	Eff.	Remov.	k(hr^{-1})	
2.0	0.0	0.00	344	215	37.5%	.235	119	99	16.8%	.092	--
4.0	0.0	0.00	344	190	44.8%	.148	119	96	19.3%	.054	--
8.0	0.0	0.00	344	160	53.5%	.096	119	107	10.1%	.013	--
12.0	0.0	0.00	344	169	50.9%	.059	119	96	19.3%	.018	--
6.0	8.7	1.33	423	93	78.0%	.253	212	36	83.0%	.296	--
16.25	7.9	1.33	336	10	97.0%	.216	189	5	97.4%	.224	--
8.0	9.4	0.75	467	67	85.7%	.243	249	18	92.8%	.328	2.3
12.0	9.4	0.75	467	42	91.0%	.201	249	13	94.8%	.246	5.3
16.0	10.3	0.72	422	49	88.4%	.135	265	18	93.2%	.168	6.1
2.0	7.5	2.28	447	178	60.2%	.460	212	87	59.0%	.445	0.2
4.0	7.5	2.28	447	81	81.9%	.427	212	34	84.0%	.458	1.8
8.0	7.5	2.28	447	39	91.3%	.305	212	13	93.9%	.349	2.7
12.33	7.5	2.28	447	30	93.3%	.219	212	2	99.1%	.378	4.6
20.25	7.5	2.28	447	16	96.4%	.164	--	--	--	--	4.9
2.0	20.9	0.71	426	227	46.7%	.315	134	47	64.9%	.524	0.9
4.0	20.9	0.71	426	134	68.5%	.289	134	7	94.8%	.738	1.3
8.17	20.9	0.71	426	73	82.9%	.216	134	7	94.8%	.361	5.5
12.0	20.9	0.71	426	--	--	--	134	9	93.3%	.225	6.7
2.0	21.4	2.22	498	246	50.6%	.353	251	88	64.9%	.524	--
4.0	21.4	2.22	498	120	75.9%	.356	251	21	91.6%	.620	2.5
7.83	21.4	2.22	498	41	91.8%	.312	251	5	98.0%	.490	5.8
12.0	21.4	2.22	498	18	96.4%	.277	251	5	98.0%	.326	8.0
2.0	17.5	2.22	504	224	55.6%	.401	230	72	68.7%	.581	--
4.08	17.5	2.22	504	115	77.2%	.362	230	26	88.7%	.545	2.0
8.0	17.5	2.22	504	40	92.1%	.317	230	9	96.1%	.405	5.7
12.0	17.5	2.22	504	18	96.4%	.278	230	6	97.4%	.304	6.5

Table 15. COD results of municipal sewage batch treatment with 24-inch RFC.

Detention time, hr	Cylinder influent, lpm	Rpm	COD (total), mg/l			COD (soluble), mg/l		
			Inf.	Eff.	Removal	Inf.	Eff.	Removal
2.0	0.0	0.00	919	433	52.9%	--	--	--
4.0	0.0	0.00	919	393	57.2%	251	200	20.3%
8.0	0.0	0.00	919	374	39.3%	251	220	12.4%
12.0	0.0	0.00	919	359	60.9%	251	209	16.7%
2.0	0.0	0.00	1,175	878	25.2%	--	--	--
10.0	0.0	0.00	1,175	732	37.7%	--	--	--
6.0	8.7	1.33	856	166	80.6%	391	104	73.4%
16.3	7.9	1.33	675	64	90.5%	300	56	81.3%
8.0	9.4	0.75	877	153	82.6%	389	73	81.2%
12.0	9.4	0.75	877	130	85.2%	389	79	79.7%
16.0	10.3	0.72	935	147	84.3%	410	84	79.5%
2.0	7.5	2.28	872	327	62.5%	312	169	45.8%
4.0	7.5	2.28	872	193	77.9%	312	113	63.8%
8.0	7.5	2.28	862	118	86.5%	312	73	76.6%
12.3	7.5	2.28	872	82	90.6%	312	62	80.1%
20.3	7.5	2.28	872	81	90.7%	--	--	--
2.0	20.9	0.71	743	397	46.6%	267	132	50.6%
4.0	20.9	0.71	743	252	66.1%	267	73	72.7%
8.2	20.9	0.71	743	145	80.5%	267	53	80.2%
12.0	20.9	0.71	743	105	85.9%	267	56	79.0%
2.0	21.4	2.22	920	423	49.7%	512	186	63.7%
4.0	21.4	2.22	920	264	65.6%	512	90	82.4%
7.8	21.4	2.22	920	132	85.7%	512	50	90.2%
12.0	21.4	2.22	920	81	91.2%	512	50	90.2%
2.0	17.5	2.22	1,131	422	62.7%	430	152	64.7%
4.1	17.5	2.22	1,131	247	78.2%	430	94	78.1%
8.0	17.5	2.22	1,131	132	88.3%	430	65	84.9%
12.0	17.5	2.22	1,131	87	92.3%	430	55	87.2%

Table 16. Average BOD_5 rate coefficients for batch treatments with 24-inch RFC.

Cylinder flow rate, lpm	Rotational speed, rpm	Total BOD_5, $k(hr^{-1})$	Soluble BOD_5, $k(hr^{-1})$
8.0	1.33	.235	.260
9.4	0.75	.222	.287
7.5	2.28	.353	.408
20.8	0.71	.273	.462
21.4	2.22	.325	.490
17.5	2.22	.340	.459

Table 17. Efficiency and removal capacities for 24-inch RFC batch treatment.

Parameter	Efficiency removal	Loading, gm/m^2-day	Total removal, gm/day
Total BOD_5	95%	12	308
"	90%	23	559
"	80%	41	886
"	70%	60	1,134
Soluble BOD_5	95%	9	231
"	90%	16	389
"	80%	33	713
"	70%	48	907
Total COD	90%	20	486
"	80%	70	1,512
"	70%	110	2,079
Soluble COD	85%	9	207
"	80%	21	454
"	70%	42	794

By expressing the RFC's organic loading and removal capacity in terms of organic load per area per time, the RFC system can be compared with RBD systems (see Table 3 for RBD surface areas). Figures 21-25 show removal efficiency as a function of daily loading per square meter of surface area. A relationship developed by Popel (1964) for RBD systems is included in the figures illustrating BOD_5 removal efficiency. Popel's curve resulted from data collected at numerous RBD systems in Europe which included secondary clarification. The soluble BOD_5 data (Figure 22) appears to correlate very well with Popel's RBD observations. Soluble BOD_5 offers the best comparison because secondary clarification has little effect on its removal. The total BOD_5 data (Figure 21) shows higher efficiency for the RFC than the RBD systems. Since the amount of BOD removal by sedimentation in the RFC system is surely less than secondary clarification, Figure 21 indicates that biological treatment in the RFC system is slightly more efficient than the RBD. Figure 23 compares data of RBD and RFC continuous flow systems. None except Popel's includes secondary clarification.

These comparisons show that the RFC is very similar to the RBD in its ability to biologically treat waste. Table 17 gives removal capacities for the 24-inch RFC.

Table 18 shows data for nitrogen removal. There are instances where total and ammonia nitrogen removal exceed 50 percent, but it is nevertheless apparent that the RFC did not produce effective nitrification. In contrast to the rotating biological disk which is operated essentially in a plus flow regime, thus achieving nitrification in the latter stages, the entire RFC biomass is exposed to approximately the same loading concentration at any one time. Visual observations revealed a uniform growth throughout the system.

Table 18. Organic and ammonia nitrogen results for municipal sewage batch treatment with 24-inch RFC.

Detention time, hr	Cylinder flow rate, lpm	Rotational speed, rpm	Organic Nitrogen, mg/1			Ammonia Nitrogen, mg/1		
			Inf.	Eff.	Removal	Inf.	Eff.	Removal
16	10.32	.72	66.5	58.8	11.6%	19.9	14.9	25.0%
8	7.54	2.28	67.0	32.5	51.5%	26.0	17.7	31.9%
12	7.54	2.28	67.0	35.7	46.7%	26.0	17.6	32.3%
20	7.54	2.28	67.0	30.8	54.0%	26.0	19.5	25.0%
2	20.86	.71	69.2	52.0	24.9%	34.1	28.4	16.7%
4	20.86	.71	69.2	51.5	25.7%	34.1	24.8	27.3%
8	20.86	.71	69.2	41.8	39.6%	34.1	21.6	36.6%
12	20.86	.71	69.2	37.0	46.5%	34.1	21.6	36.6%
2	21.44	2.22	57.9	43.4	25.0%	42.3	33.1	21.8%
4	21.44	2.22	57.9	37.4	35.4%	42.3	30.4	28.1%
8	21.44	2.22	--	42.4	26.8%	42.3	25.1	40.7%
12	21.44	2.22	--	--	--	42.3	20.2	52.3%

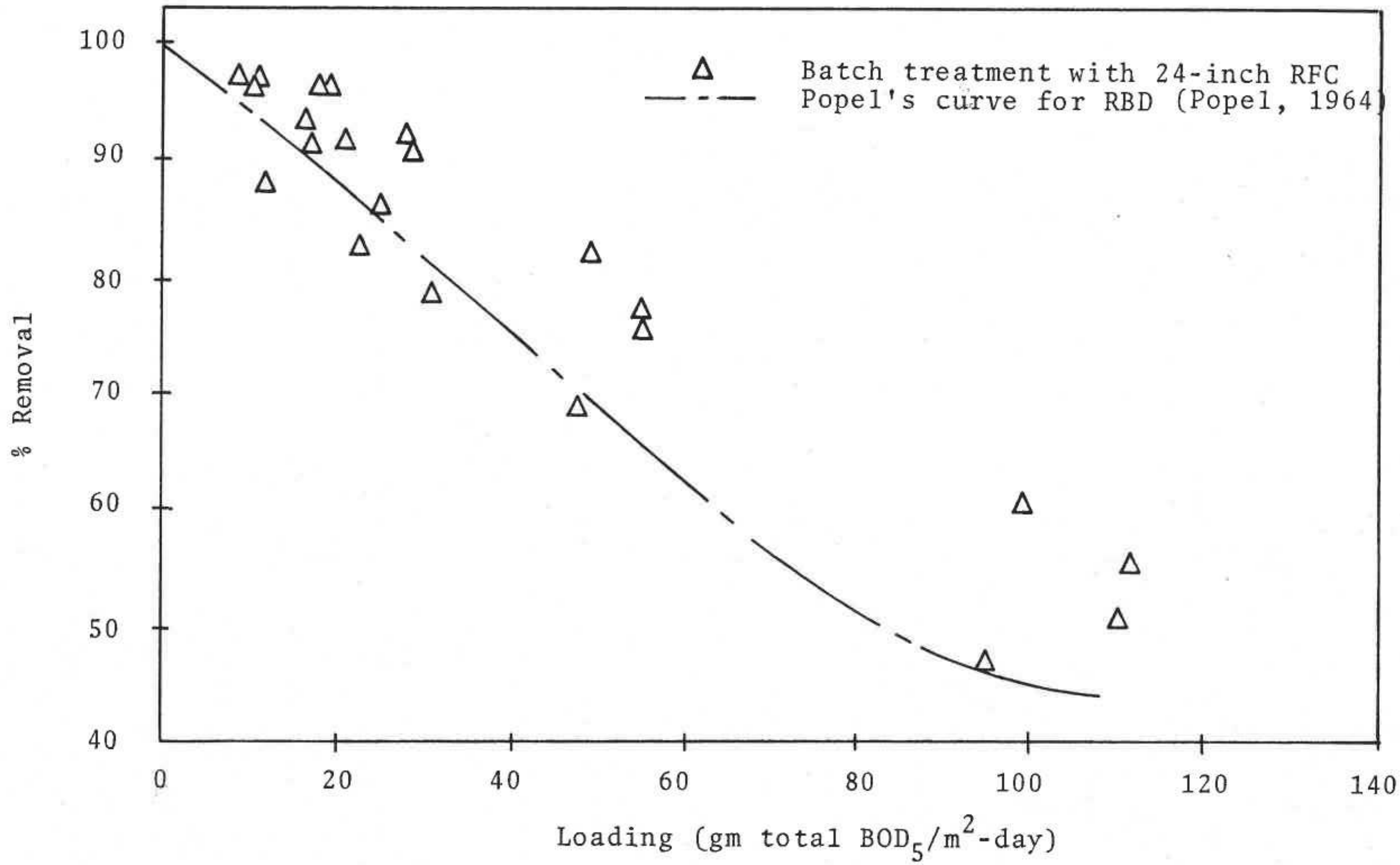

Figure 21. Efficiency of BOD_5 removal vs BOD_5 loading for 24-inch RFC.

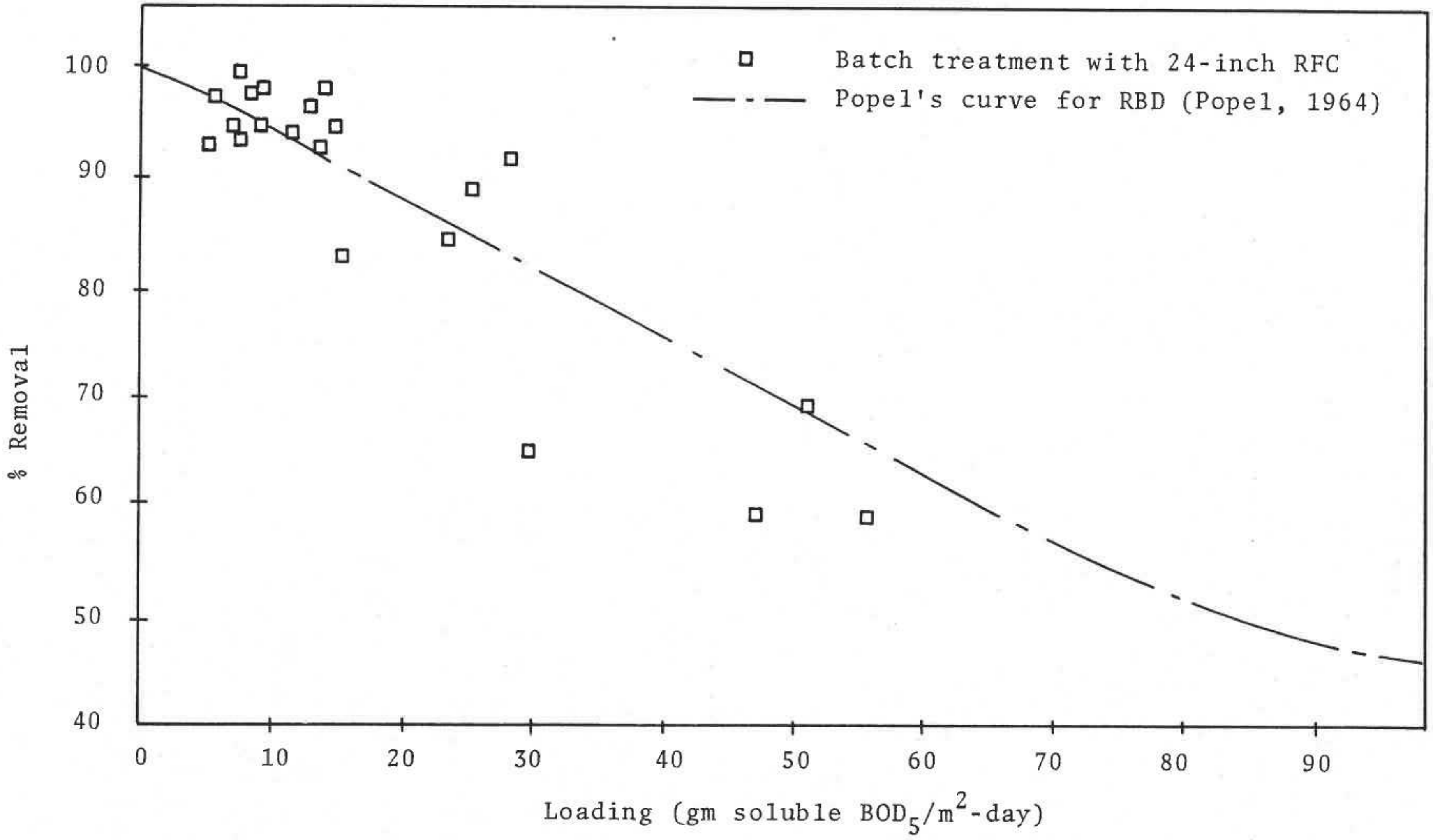

Figure 22. Efficiency of BOD_5 removal vs BOD_5 loading for 24-inch RFC.

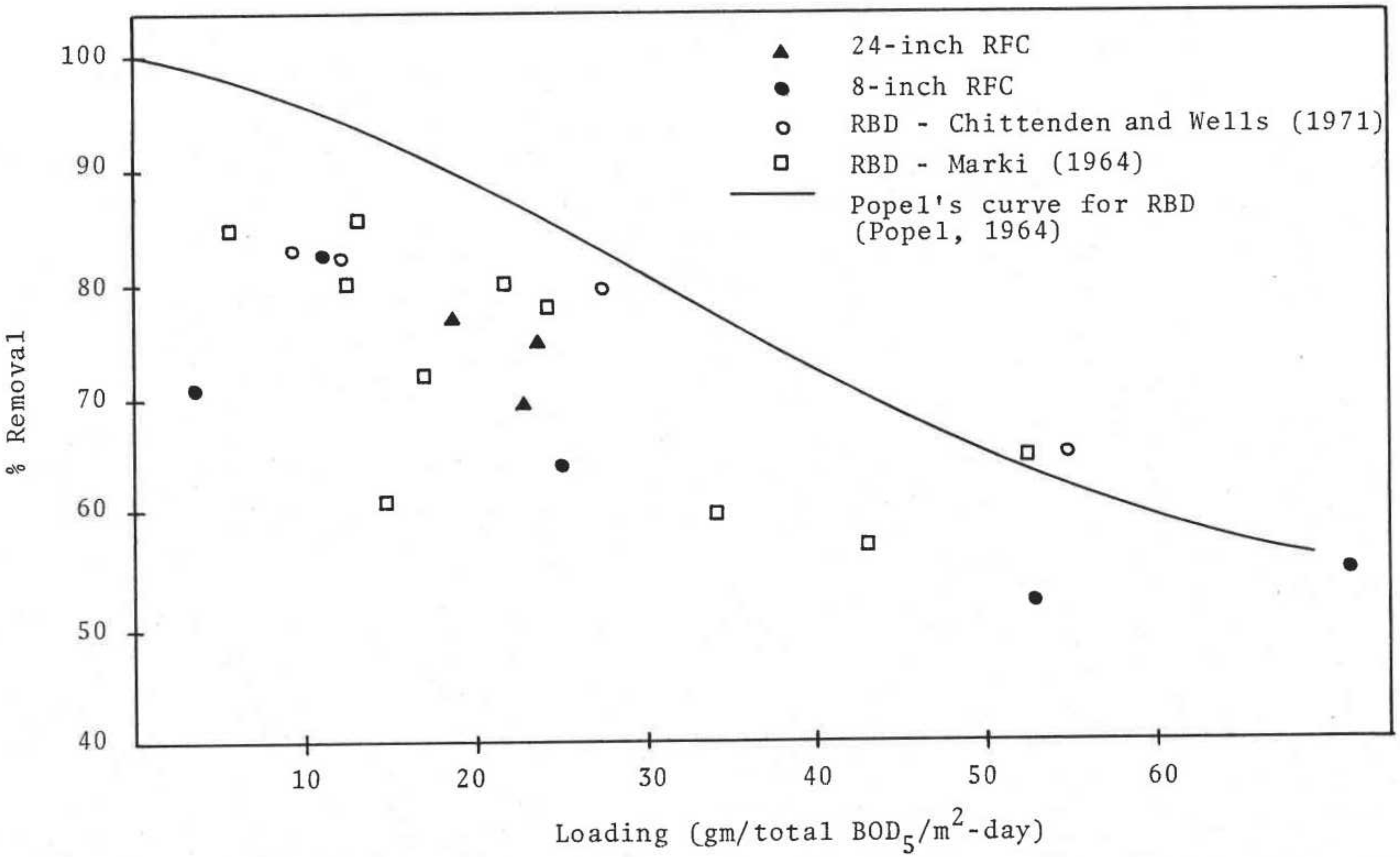

Figure 23. Efficiency of BOD_5 removal vs BOD_5 loading for continuous flow with RFC and RBD systems.

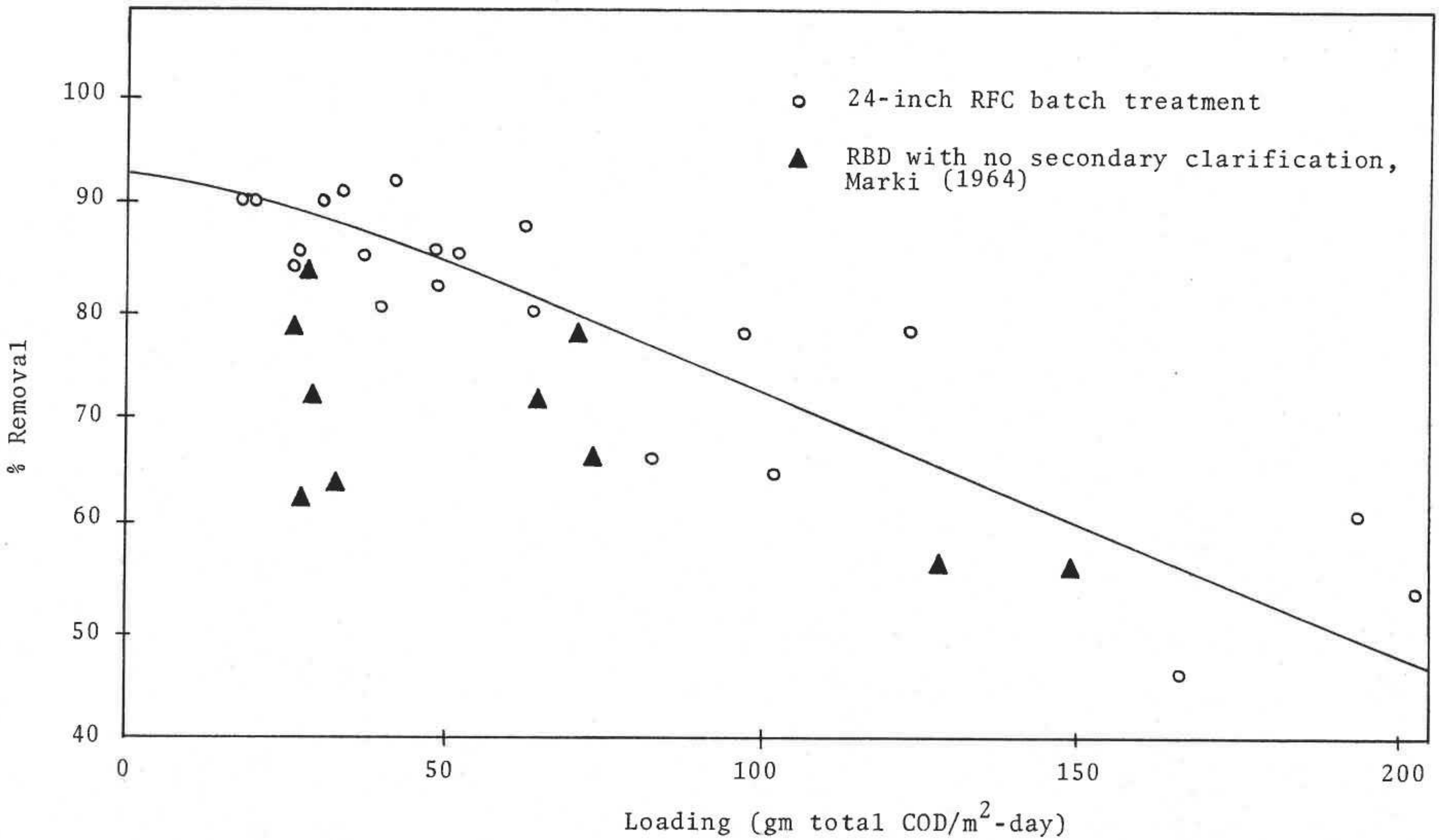

Figure 24. Efficiency of COD removal *vs* COD loading for 24-inch RFC and RBD systems.

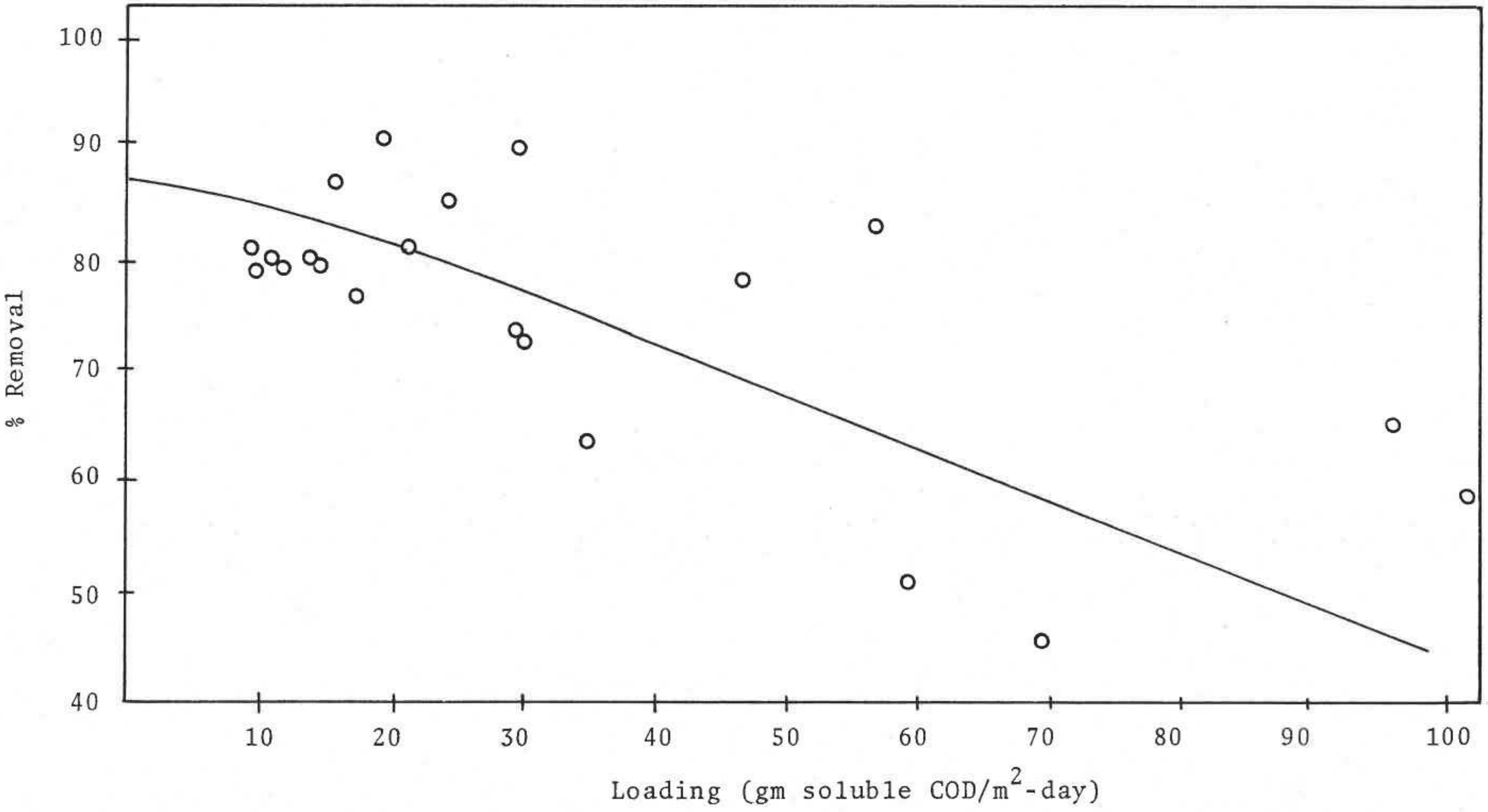

Figure 25. Efficiency of COD removal vs COD loading for 24-inch RFC.

At long detention times when BOD concentration becomes low, favorable circumstances for nitrifiers exist. The absence of nitrification during these times is perhaps due to insufficient time to establish a viable population. There was some indication of nitrification, although by no means conclusive, during operation of the 8-inch RFC. Because of storm water dilution, the raw sewage BOD concentration was in the range of 20 mg/l. A continuous flow result showed the effluent BOD to exceed the influent BOD by a few mg/l, a situation simultaneously experienced by the trickling filter plant next door and attributed to nitrification.

Cost considerations for an RFC unit are only speculative, but appear to compare favorably to other package plant operations. By estimating unit power cost at $.01/kw-hr and power consumption at .27 kw, a total annual power cost of $56 is computed. Because of the low care required, any maintenance could be easily integrated into the existing establishment being served. Capital costs are estimated to be below $2,500 based on experience with the 24-inch model. From examination of the costs, an RFC unit offers a competitive alternative to existing small treatment plants.

CONCLUSION

The rotating flighted cylinder was tested as both a solid-liquid separator and as a biological waste treatment device. As a solid-liquid separator, it was demonstrated to be effective in removing settleable particles from a dilute slurry and concentrating them into a low volume concentrated stream. As a biological waste treatment device, it effectively combined primary and secondary waste treatment into a single unit and produced an effluent comparable to that obtained from conventional secondary sewage treatment devices. The main advantages of this device are its mechanical simplicity, low power consumption, and trouble-free operation.

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APPENDIX A

SAMPLING AND ANALYTICAL PROCEDURES USED TO EVALUATE THE 8- AND 24-INCH RFC UNITS WHEN USED TO TREAT DOMESTIC SEWAGE

Sampling during batch treatment was done in one-liter pyrex reagent bottles. Influent samples were collected from the line discharging raw sewage into the system. Treated samples were collected from the effluent barrel by submerging a sample bottle sufficiently to allow wastewater to flow gently into the bottle.

Composite samples over an eight or nine hour period were taken during continuous flow treatment after the system had run approximately 16 hours. Influent was collected as it entered the influent barrel and effluent was collected as it left the effluent barrel. These samples were collected in a 250 ml graduated cylinder and immediately added to the composite sample in a one-liter pyrex bottle at 3^{o} C.

Sampling for solid-liquid separation was accomplished by collecting samples every ten minutes for one hour from the influent to the upper cylinder end, the lower cylinder end effluent, and the augered effluent. During operation of the 8-inch cylinder, 50 ml samples were taken and 150 m samples were used for the 24-inch cylinder. The samples collected over the sampling period were composited separately for each of the three collection points.

Dissolved oxygen samples during treatment were collected from the barrels in 300 ml BOD bottles by submerging the bottle just enough to allow wastewater to flow gently into the bottle until completely full.

Five-day BOD and COD tests were run according to <u>Standard Methods</u> (APHA, 1971), with the azide modification of the Winkler method used to determine dissolved oxygen in the BOD test. Both total and soluble samples were analyzed. Total samples were well-mixed aliquots of the samples as they were collected, whereas soluble samples consisted of the filtrate of a total sample filtered through a GF/C 5.5 cm Whatman glass fibre filter paper.

Kjeldahl nitrogen was determined according to <u>Standard Methods</u> (APHA, 1971) except 100 ml. Micro-Kjeldahl flasks were used instead of 800 ml Kjeldahl flasks. Digestion was accomplished with 10 ml of sample and 10 ml of digestion reagent boiled approximately 30 minutes beyond the cessation of visible white SO_3 fumes. The sample was then diluted by adding approximately 30 ml of distilled water and 10 ml of hydroxide-thiosulfate to raise the pH. The digested samples were steam-distilled until approximately 20 ml were collected in boric acid. The boric acid and distillate were then measured and analyzed for ammonia concentration by Nesslerization and colorimetric determination with a Coleman Junior II Spectrophotometer, Model 6-20.

Ammonia nitrogen concentrations were measured by clarifying a 100 ml sample with $ZnSO_4$, raising the pH to ten with a NaOH, and centrifuging at rpm for 15 minutes. The supernatant was then nesslerized and ammonia concentration determined with the Coleman spectrophotometer.

Suspended solids determinations were made by filtering a measured volume of sample through a previously dried and weighed GF/C 5.5 cm Whatman glass fibre filter paper and drying for a minimum of four hours at 100° C.

Total solids and total volatile solids were analyzed according to Standard Methods (APHA, 1971).

The azide modification of the Winkler method was used to find dissolved oxygen concentration on samples immediately after collection.

Analyses of BOD, COD, Kjeldahl, and ammonia nitrogen were performed on samples that had been stored at 2° C for one to three days. All solids determinations were done within hours after collection of the sample.

BOD samples were run in triplicate, and COD and suspended solids samples in duplicate. For ammonia and Kjeldahl nitrogen, one sample was prepared for colorimetry and three dilutions were then measured spectrophotometrically. Values were averaged, except that any results of triplicate analyses deviating sigsignificantly (approximately 50 percent) from the accompanying samples were discarded.

APPENDIX B

DAIRY MANURE SLURRY TREATMENT

The 8-inch PVC tube previously used for oxygen transfer studies was used for treatment of liquid dairy manure at two loading rates. This treatment is shown in Figure 13. The barrel was used as a storage tank. Effluent was removed from it once a day; feed slurry was added to it after effluent removal. The air lift pump continuously transferred barrel contents from near the bottom of the barrel to the rotating flighted cylinder at a point about 30 cm from the upper end. Both upper and lower effluent streams were discharged to the barrel. This arrangement of equipment is similar to that which would result if a rotating flighted cylinder were placed over or adjacent to an existing manure storage tank receiving flushes of liquid manure on a daily basis.

Samples of these studies were obtained by collecting a supply of fresh dairy manure from the OSU Dairy Barn in a large metal container, mixing to assure homogeneity, and packaging in 100 and 200 g units in plastic freezer bags. The manure samples were stored in a freezer until the day of use.

The treatment system was fed and sampled daily Monday through Friday. Samples of effluent and feed were analyzed immediately using procedures from Standard Methods (APHA, 1971), facilitated with supplies from Hach Chemical Company where appropriate.

FIVE HUNDRED GRAM PER DAY STUDIES

In the first dairy manure study, 500 g of manure were fed and 20 l of effluent removed daily. Immediately after removing 20 l of effluent from the top of the barrel, four 100 g manure packets were added. A fifth manure packet was mixed with 4 l of water to provide the feed sample for analyses. After the necessary samples were obtained, the residual was added to the barrel and the liquid volume returned to 175 l by the addition of water.

During this trial, it was evident that the system was operating satisfactorily by the lack of odors and the generally desirable-appearing effluent. At the end of this three-week trial, it was concluded that the full capability of the device was not being utilized. A portion of the removal that was being achieved was due to solids settling and accumulating in the barrel.

ONE THOUSAND GRAM STUDIES

This trial was conducted in a manner similar to the one above, except that 200 g packets were fed and 40 l of effluent were removed daily. In order to prepare a feed sample, a 200 g packet of manure was mixed with 8 l of water. Thus, the system was loaded at twice the previous rate.

Again, the device was able to accept the applied waste load for a four-week period, maintain an aerobic environment, and yield an effluent showing 60 to 90 percent pollutant reduction depending upon the constituent of concern. In this trial, the loading rate was near the maximum acceptable if maintaining aerobic conditions in the barrel is essential. Although dissolved oxygen was present in the barrel, concentrations were frequently less than 1.0 mg/l during this study. The thickness of foam on the barrel increased to about 6 cm during this trial, but no complications resulted. Heavier solids accumulated in the bottom of the barrel as before.