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ABSTRACT

A laboratory study was carried out on a new concept for treating domestic wastewater. It uses a septic tank as an anaerobic digester, and a circulation loop which has a pump and a semipermeable membrane module. The flux was maintained by a cyclic operation for a flat sheet membrane module for 1500 hours, and 8300 hours for a Helicore Module. Not only were the turbidity and E' coli count zero in the effluent, but 85 to 95% BOD and 75% nitrate reduction were also observed. Phosphate reduction also occurred, but the reason for it is not clear. These results are encouraging enough to recommend further work.

INTRODUCTION

In rural areas, the usual method of domestic sewage treatment is a septic tank with a leach field or drain field. Although the tank acts as a crude anaerobic digester, very little digestion occurs other than liquifying solid organic wastes because the average residence time in the tank is only one or two days. The major purification of the water occurs in the leach field as the effluent from the septic tank percolates through the field. When sufficient soil percolation is provided where the combination of chemical, physical and biological purification mechanisms take place, the water is generally free of pathogens, suspended solids, and is low in biological oxygen demand (BOD). However, minerals are left, except where the soil has ion-exchange capabilities.

When the system works, it offers a cheap, safe and reliable method which is generally flexible with regard to the daily load imposed upon it. The real objection to a septic tank is due to the lack of proper soil percolation.(1) As a result, a laboratory investigation was carried out to explore the feasibility of a system using a septic tank and a semipermeable membrane module. Since the water purification takes place as the water passes through the membrane, the system is not dependent upon the soil percolation characteristics for its success. The investigation focused on three major areas: (1) ways to maintain a practical flux through the membrane over months of operation, (2) the effect on the biological activity in the septic tank caused by the change in concentration of microorganisms, organic material, and ions resulting from the use of the membrane, and (3) the water quality of the effluent as a function of membrane rejection.

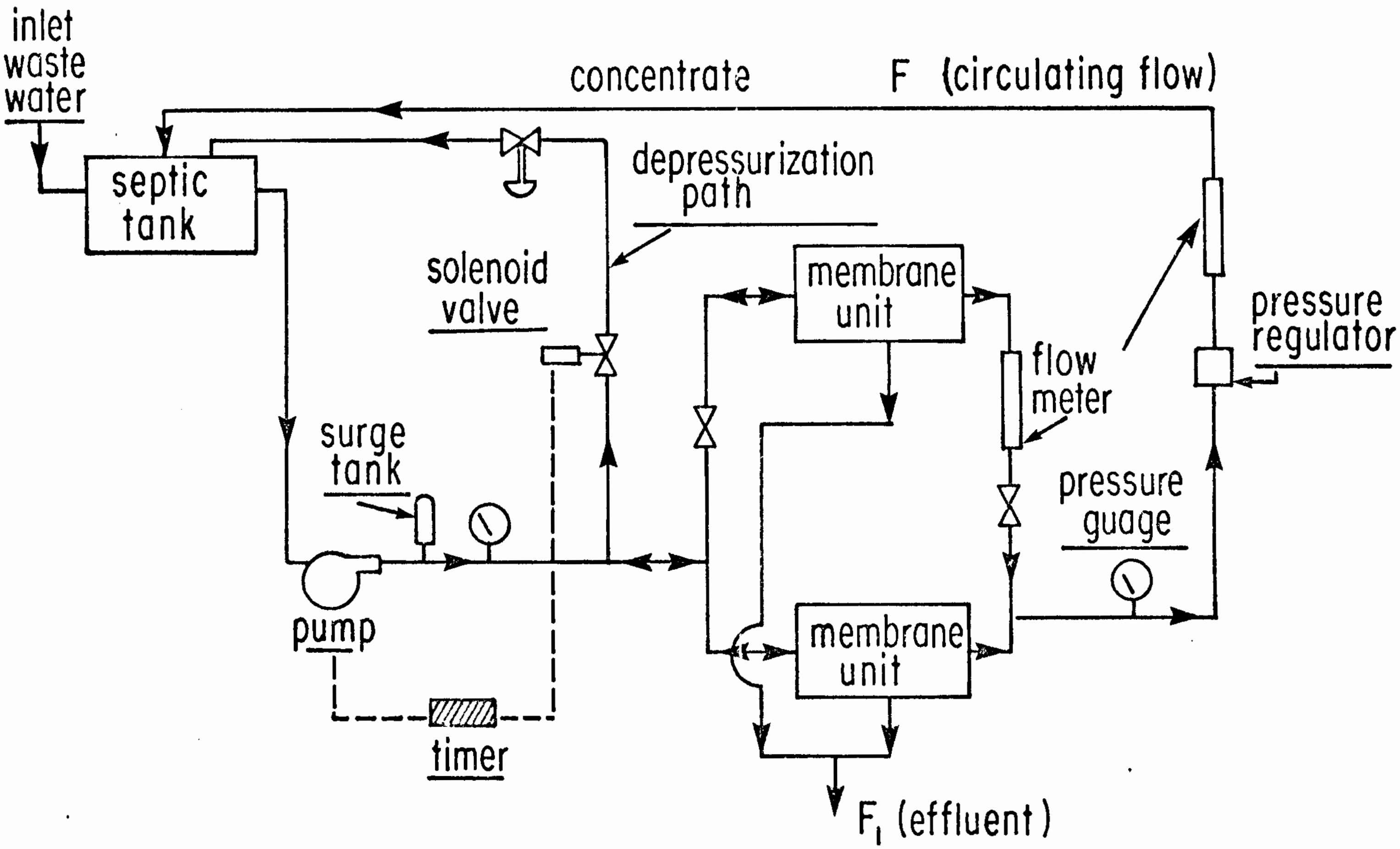
SYSTEM DESCRIPTION

A schematic diagram in Figure 1 shows the major components used in the laboratory system. A two-compartment rectangular tank with a total volume of 28 gallons (108 liters) was constructed of plexiglass to allow visual inspection of the sludge level in the tank. With a second stage, solid settling is promoted. The tank was fitted with a black polyethylene cover, which was used routinely to keep the tank in the dark except when observations were made.

The pressure for the water permeation through the membrane is supplied by a Milton-Roy variable stroke positive displacement piston pump with a maximum flow rate of 42 gallons per hour. Operating pressures were in the range of 50 to 150 psig. A small surge tank following the pump evens out the flow pulses. The flow is directed to one or two modules in parallel, and the concentrated solution is returned to the first stage of the septic tank. The pressure on the membrane module is maintained by a back pressure regulator. The purpose of the depressurization path will be discussed later.

Two types of membrane modules were used. The first was a flat sheet membrane module which has a total exposed membrane area of 0.0729 sq.ft. The flow channel is 10.5 inches long, 1.0 inch wide, and 0.015 inch high. Since the flow channel was cut into a solid piece of plexiglass, it is possible to view the membrane surface during the operation. The second was a commercial product from the Universal Water Corp., called a Helicore reverse osmosis unit. It consists of six porous tubes with the membranes wrapped around the outside of the porous tube. These tubes are mounted inside stainless steel tubes, such that the flow in the annuli is connected in series, and the water that permeates through each porous tube can be collected separately.

During laboratory runs, 3 to 5 gallons of fresh sewage was added to the first stage of the septic tank per day. The sewage was obtained at the inlet of the Hanover sewage treatment plant and transported to the laboratory in a



PRESENT TEST SYSTEM FOR SEPTIC TANK EFFLUENT TREATMENT

FIGURE 1

glass carboy.

In an ordinary septic tank, the effluent is displaced by the influent. This overflow arrangement maintains a constant liquid volume in the tank. In the present system, the effluent rate is determined by the water permeability through the membrane. Since this rate does not instantaneously match the influent rate, liquid level in the tank varies throughout the day. By using the surge capacity of the septic tank, the average volumetric flow rate of inlet and outlet are matched.

The gas formed in the septic tank is vented and collected by water displacement in a glass carboy. Total daily gas production volume is determined when the liquid level in the septic tank is brought to a standard reference level and the pressure adjusted to 1 atmosphere.

In order to provide control of concentration polarization at the membrane surface and to mix the content of the septic tank, the circulation flow F is much larger than the effluent rate F_1. In some runs, it is as much as 200 times larger.

FLUX MAINTENANCE

Since the water passing through a fresh membrane has a quality superior to conventionally treated effluent, semipermeable membrane techniques have been investigated in the laboratory[2,3] and the pilot plant[4] to develop their potential. While membrane techniques have been used, either on filtered primary or aerobic secondary treated effluent, the major operating problem of flux maintenance and membrane durability were also expected to be present with an anaerobic system such as in a septic tank.

Flux decline is caused by the compaction of the membrane under pressure and by the accumulation of deposits on the membrane surface.[7] While the first cause is minor in the pressure range of interest, the latter is a serious problem because the fluid passing over the membrane surface contains suspended solids and microorganisms as well as dissolved solids.

The importance of bulk velocity past the membrane surface as a way to retard flux decline is shown by the data of Feurstein[5] in Table 1 for the continuous treatment of primary effluent in a tubular reverse osmosis module run at 700 psig.

Table 1. FLUX DECLINE AS A FUNCTION OF BULK VELOCITY[5]

Bulk Velocity	Flux decline in gal/day/ft^2
2.58 ft/sec	23 to 3 in two days
6.45 ft/sec	23 to 3 in seven days
12.9 ft/sec	23 to 16 in 14 days

Only by using a velocity of 12.9 ft/sec could reasonable flux levels be maintained for two weeks. While these results are specific for the waste water studied, a general observation is that each material processed by a semipermeable membrane module has a critical bulk velocity below which the membrane fouling rate is markedly increased and unacceptable.

Fisher and Lowell[6] found that they could maintain 80% to 90% of the initial flux over a 5-day test period with secondary effluent by daily cleaning the membrane with an enzymatic laundry pre-soak.

Since the concept of a septic tank/membrane system will be applied in a rural home, the operating costs and operator attention must be kept at a minimum. Therefore, high circulation velocity, which increases the pumping cost, and daily membrane cleaning are not useful methods in this application for flux maintenance.

When using the plexiglass flat sheet reverse osmosis module, it is observed that some of the solid material floats off the surface of the membrane when the pump is shut off and the pressure released. This backflow is caused by the osmostic pressure difference between the relatively pure water on the one side of the membrane and the impure water on the septic tank side, and tends to clean the membrane. In fact, Feurstein[5] reported that the flux increased after a daily shutdown for 15 minutes. However, this recovery was quickly reduced to the previous value, and the effect of the shutdown is lost. The notion that the operating cycle should be short -- in the order of minutes followed by a rest period -- is a new idea that was tried here.

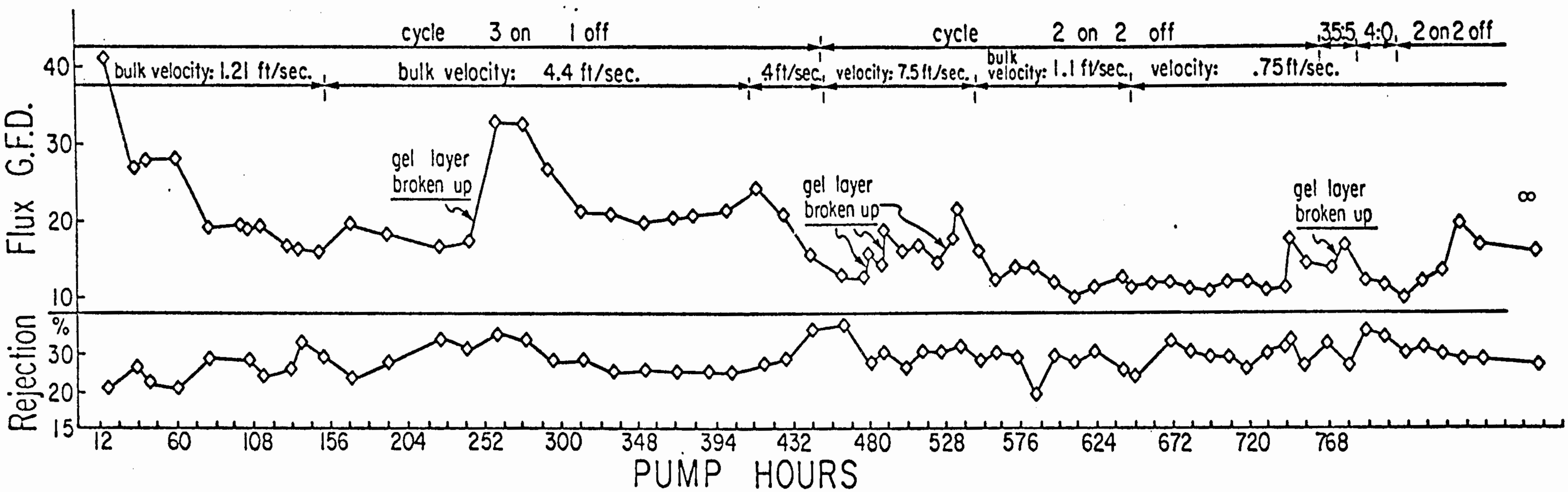
The equipment shown in Figure 1 was modified to include a timer switch for the pump which could be set by adjustment to be on for any part of up to a 4-minute cycle. When the pump is switched off, the timer simultaneously opens a solenoid-operated valve in the depressurization path to quickly release the pressure in the module to 0 psig. By having the depressurization path, the pressure in the module drops quickly, which immediately promotes backflow; and locating the path on the upstream side of the module encourages the backflow to dislodge particles which are jammed into the module flow channel.

It is now necessary to determine how the operation (that is, how long the pump should be on with the membrane module under pressure, and how long the pump should be off with the module at 0 psig) and the bulk flow rate are related to the flux decline. The performance of the flat sheet membrane module is shown in Figure 2, which gives the flux (gal/ft^2 of membrane per day or gfd) during the "on" part of the operating cycle, and the percent ionic rejection (as determined by conductivity) vs pump hours (accumulated time that the pump was on).

At the end of the test, 900 pump hours correspond to 1500 hours of elapsed time.

Also shown on the figure are the bulk velocities and the operating cycle used during the test. The cycles are characterized by two numbers separated by a colon. Thus, 3:1 means 3 minutes on and 1 minute off; 4:0 means continuous run with no off period, etc.

For a given cycle, the average flux is increased with increased bulk



Effect of operating cycle and bulk velocity on Flux and Ionic rejection for flat sheet membrane module.
(OPERATING PRESSURE 150 psig)

FIGURE 2

velocity. For example, for the first 156 hours with a bulk velocity of 1.21 ft/sec, the initial flux drops from 40 to 20 gfd in about 80 hours, which is typical of a new membrane. Then the flux declines more slowly to about 15 gfd at 156 hours. When the bulk velocity is increased to 4.4 ft/sec, there is an immediate increase in flux to about 20 gfd followed by a period of slow flux decline.

At 240 hours, a very unexpected but typical behavior of cyclic operation occurs. The solids which build up on the membrane surface can be seen through the plexiglass module, and appear to cover the membrane with a black gel. The gel layer spontaneously breaks off with an increase in flux of about 32 gfd, and the appearance of the membrane surface is clean. This is followed by a period of relatively rapid flux decline which is typical of a clean membrane, so that by 312 hours the flux is back to 20 gfd. Now there follows a period of relatively constant flux to about 418 hours.

At this time the bulk velocity is decreased to 0.4 ft/sec with the immediate effect that the flux steadily declines. At 456 hours, the operating cycle is changed to 2:2, and the bulk velocities increased slightly to .75 ft/sec. We notice that the flux tends to level out from its previous rapid decline, and after 480 hours the gel layer breaks off with an immedicate increase in flux. From 552 to 720 hours, there is a period of rather constant flux of about 12 gfd even though the bulk velocity was changed to 1.1 ft/sec and turned back to 0.75 ft/sec. Then there is a period of gel breakup and increasing fluxes.

It appears with the 2:2 operating cycle it is possible to maintain a steady flux of about 12 gfd with the bulk velocity as low as 0.75 ft/sec. Note that when the cycle is made continuous at 792 hours, for the period of a day the flux declines and can be recovered when returned to the 2:2 cycle.

From these observations, several qualitative features of the cyclic operation can be identified, First, when the membrane surface is free of deposit, the flux is high and the gel layer initially accumulates at its highest rate. During the off period of the cycle when the backflow occurs, some noticeable solids are floated off the membrane surface, but not enough to clean the entire surface. As the flux declines, the rate of accumulation decreases, and in effect, a steady state gel layer is developed. This behavior distinguishes the cyclic operation from the continuous operation where the flux declines monotonically with time, and in some cases may level off but then at very low impractical flux levels. The spontaneous but unpredictable breakup of the gel layer must be due to the mechanical effects of the changing pressure and velocities.

For a given operating cycle, the value at which the flux finally levels off depends on the bulk velocity -- the level being higher for the high velocity. However, there is a minimum bulk velocity that is required. In Figure 2 it is clear that the bulk velocity of 0.4 ft/sec does not lead to steady flux for the 3:1 cycle, while 1.21 ft/sec seems to give a flux of about 15 gfd, and 4.4 ft/sec gives a flux of about 22 gfd. On the other hand, the 2:2 cycle, which allows more time for backflow, can give a steady flux of about 12 gfd with a bulk velocity as low as 0.75 ft/sec. Note that these are practical flux levels achieved with modest bulk velocity.

Finally, the spontaneous breakup of the gel layer, which results in cleaning the surface of the membrane, is a self-cleaning method unique to the cyclical operation procedure, and in the long run is probably the most important mechanism for achieving long-term practical flux levels. It should be pointed out that the nature of the gel layer, and its physical changes as it accumulates and peels off the surface, is very dependent on the nature of the fluid being processed. As a result, these observations may or may not be applicable to treating other materials with membranes.

In a second membrane test with a Helicore module, essentially three different membrane porosities were used as shown in Table 2, which allowed for the evaluation of water quality parameters as a function of membrane rejection. Tubes 1 and 2 have a sodium chloride rejection of 45% to 50%. Tubes 3 and 4 have about 70%, and Tubes 5 and 6 have about 80%.

Table 2. COMPARISON OF FLUX FOR SIX TUBES OF HELICORE R.O. MODE IN CONTINUOUS AND CYCLIC OPERATION

		Continuous Operation		Cyclic Operation				
Tube No.	Initial NaCl Rejection	Initial Flux gfd	Flux gfd	Restored Flux gfd	Flux gfd	Flux gfd	Flux gfd	Final NaCl Rejection
1	49%	9.86	1.81	8.34	4.67	3.85	2.90	44%
2	45%	11.84	1.49	7.45	3.95	2.62	1.20	42%
3	75%	6.65	1.67	6.94	3.61	2.74	1.75	65%
4	69%	7.86	1.72	6.54	3.78	3.26	1.42	66%
5	81%	5.96	1.76	5.40	3.71	3.30	1.64	75%
6	81%	5.71	2.37	5.02	3.19	2.93	3.05	76%
Real Time, hr		0	160	0	664	2300	8400	
Accumulated Pump Time, hr		0	160	0	355	1180	3330	

The initial test of this unit was under continuous operation for 160 hours at 150 psig, with a septic tank fluid at a bulk velocity of 4 ft/sec. By comparing the initial flux with the flux of 160 hours, it is clear that the flux drops off rapidly, especially for those tubes with the highest initial flux. Moreover, the slope of the flux time curve is quite negative which indicates that a steady-state flux will not be established on further continuous operation.

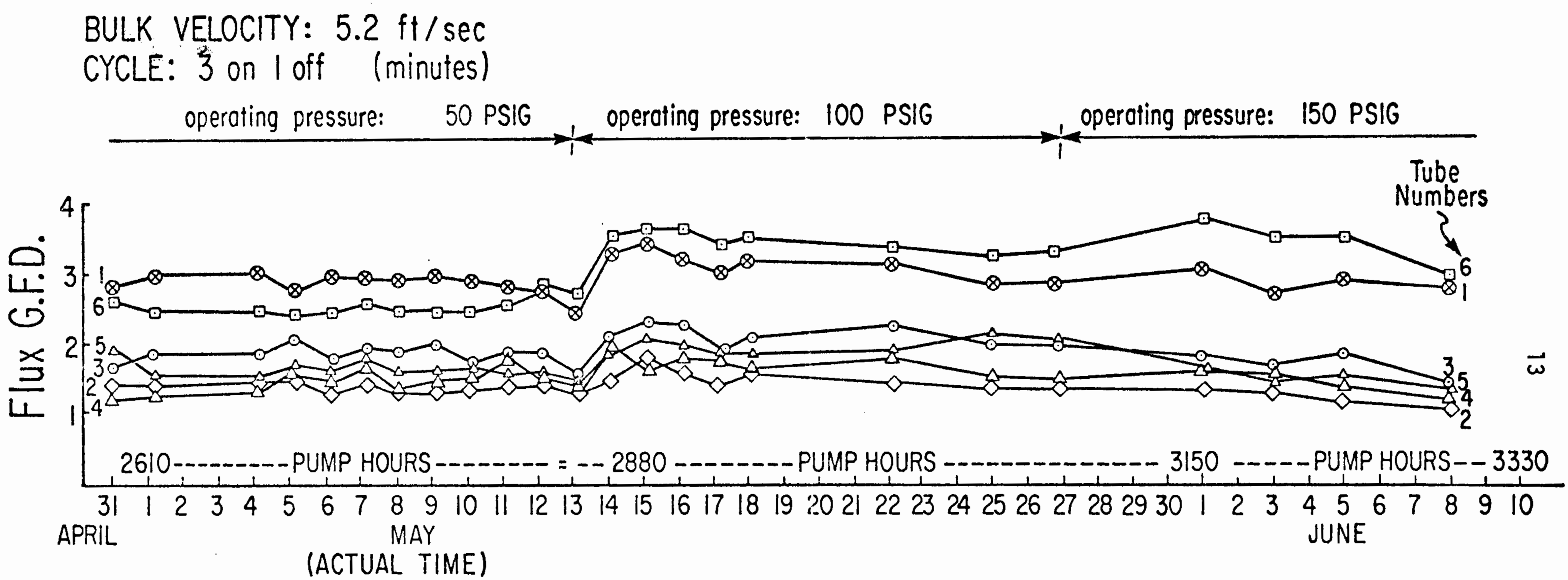
The unit was cleaned by washing off the accumulation on the membrane surface with a stream of water, and reassembled. But this time the operating cycle was introduced. Parametric studies were carried out on the operating cycle and the bulk velocity over several months. Of course, it was not possible to observe the membrane surface during the run.

The general behavior was similar to that shown in Figure 2 for the flat sheet membrane, except for flux levels as a whole were lower, and the rejection higher. Table 2 gives the restored flux after the module was cleaned and after 664, 2300 and 8400 hours real time, corresponding to 335, 1180 and 3330 hours of accumulated pump time.

Figure 3 shows the data for the last three months of operation of the Helicore module. Here the effect of the operating pressure is shown for a 3:1 cycle in a bulk velocity of 5.2 ft/sec. After 2600 pump hours, the pressure was set to 50 psig from the previous 150 psig; then at 2800 pump hours the pressure was increased to 100 psig, and finally at 3000 pump hours the pressure was returned to 150 psig. While there is a slight increase in flux with pressure, especially for the higher flux tubes, the major point of interest is that the flux levels for all the tubes are rather constant. In short, a steady-state operating flux has been reached which is not extremely sensitive to pressure in the range studied.

When comparing the flux levels after 3330 pump hours with the initial flux of the Helicore unit, it is clear there has been a steady flux decline from the initial value, but this same drop in flux can occur in just 160 hours of continuous operation. Moreover, the slopes of the flux - time curves in Figure 3 are flat during this extended period of operation. Obviously, the system could have been operated beyond this time.

It should be noted that the flux from each tube of the Helicore module was lower than the expected flux from a flat sheet membrane module with the corresponding rejection. For example, our flat sheet membrane with 45% to 50% rejection would have an expected flux of about 25 gfd, compared to about 10 gfd for the Helicore tubes #1 and 2. This difference in performance is due to the artifacts of membrane casting. While the details of the manufacture of the Helicore module are not known, the flat sheet membrane was made



Effect of operating pressure on flux through the Helicore Tubes

FIGURE 3

in our laboratory under conditions[8] which maximize the flux for a given rejection level, which accounts for its superior performance.

During the entire time that the module was in operation, it was shut down twice for an extended period of time, once for seven days and once for fourteen days. Membrane unit was not flushed clean of the septic tank fluid during the shutdown; only the pump was shut off and the pressure released. As a result, the test fluid was in contact with the membrane. Since the rejection level of each tube remained similar to its initial value, the microorganisms in the fluid did not cause any noticeable damage to the membrane. While this experience is contrary to other workers', it may be because the system is anaerobic rather than aerobic. Referring back to Figure 2, the ionic rejection of this test varied from the initial value of 21% to a final value of 24.5% after 906 hours. Again, we conclude cellulose acetate did not deteriorate in the anaerobic environment.

The significance of the flux maintenace study is that the feasibility of the cyclic operation is demonstrated as a practical way to maintain the flux in the presence of suspended solids. The flux does decline with time until an approximate steady-state value of one-third to one-fourth of the original flux is reached. This steady-state flux is maintained by the hydrodynamic action of the flow under cyclic operation. Moreover, the bulk velocity may be reduced to one-third to one-tenth of that recommended for continuous operation, which is important in reducing the pumping cost.

WATER QUALITY

The water quality of the effluent is primarily controlled by the selection of the membrane porosity. Membranes with relatively large pores, in the range of one hundred to ten thousand angstroms, are called ultrafiltration membranes, since they physically hold back the macromolecules which are too large to pass through the pores. Membranes of small pores, in the range of ten to forty angstroms, are called reverse osmosis membranes. Here, separation of ions is possible by the interaction of the solvent, solute and membrane material. The porosity of reverse osmosis membranes is conveniently expressed as a fraction rejection of a test electrolyte, such as 1% sodium chloride. When the module is undergoing tests with sewage, the total ion rejection of the membrane is determed by one minus the ratio of the conductivity of the effluent to that of the solution in the septic tank.

In this application, a reverse osmosis membrane was investigated because a certain amount of ionic rejection of the nitrate and phosphate was thought to be desirable, while at the same time the membrane would act as an ultrafilter for the macromolecules, colloids, bacteria, and viruses. During the flux decline studies, some data were collected on the water quality of the effluent. Although the data were limited, and reflected variations caused in part by the accumulation and breakup of the gel layer on the membrane and the daily variation in the influent, Table 3 gives figures averaged over a six-week period of operation for the inlet, the septic tank fluid, and the effluent from the Helicore module tubes No. 1, 3, and 6. Since the rejection of the membrane increases with the tube number 1, 3, and 6, respectively (refer to Table 2), the total ion concentration (as measured by conductivity), BOD, nitrates, and phosphates in the effluent all decrease with increasing membrane rejection. There was a slight odor of H_2S associated with the product which is removed by aeration. The presence of H_2S was confirmed by a positive indication with lead acetate paper.

By taking tube No. 3 as typical of the mixed average effluent of all six tubes from the Helicore module, the septic tank membrane system can give a BOD reduction of about 90%, and all of the remaining BOD is in a soluble form. Since the effluent is clear with zero turbidity, and free of E coli, water of

Table 3. AVERAGE WATER QUALITY PARAMETERS AT VARIOUS POINTS IN THE SEPTIC TANK - MEMBRANE SYSTEM

Stream	Conductivity micro mohs/cm	B.O.D. mg/l	% Reduction	Nitrate mg/l N	% Reduction	Ortho Phosphate mg/l PO_4	% Reduction	Turbidity JTU	E Coli no/ml
Influent	410	270		3.5		33		108	
Septic Tank Fluid	830	140		2.2		87		650	
Effluent from									
Helicore Tube No. 1	430	40	85%	.98	72%	25	24%	0	0
Helicore Tube No. 3	380	29	89%	.88	75%	20	39%	0	0
Helicore Tube No. 6	170	17	93%	.95	73%	5	85%	0	0

this quality can be discharged into nearby surface waters, or sprayed on vegetation. In fact, where the soil percolation is not adequate for water purification of a normal septic tank effluent, underground disposal is a possibility that should be considered, since no suspended solids are present which are one of the major causes of the failure of leach fields. An interesting feature of this system is that it gives a reduction in the nutrient levels of nitrate and phosphate in the effluent, as will be discussed in the next section.

THE EFFECT OF THE MEMBRANE ON THE SEPTIC TANK

The waste water in the septic tank is a multicomponent aqueous fluid of solutes, microorganisms and suspended solids. For a given membrane, some components will pass completely through the membrane, some will be partially rejected, and still others will be completely rejected. As a result, the combination of the septic tank and the flow loop with a membrane module has some interesting and desirable properties which are not achieved in the normal septic tank.

Since the membrane porosity is chosen so that the macromolecules, the microorganisms, the large organic solutes, and suspended solids cannot pass through it, these materials are retained in the septic tank. However, they do not accumulate indefinitely, because the increased concentration of the organics and microorganisms causes an increase in the rate of organic decomposition. As a result, most of the organic carbon eventually leaves the system as carbon dioxide and methane resulting from the anaerobic digestion. A small amount leaves through the membrane as soluble organics which is indicated by the low BOD in the effluent. The refractory organics, which accumulate in the sludge, represent that part of the inlet flow which is not attacked by the microorganisms.

In contrast to a normal septic tank, microorganisms, organic solutes, and suspended solids leave the tank with the effluent flow at the average respective concentration of these materials in the tank. As a result, relatively little digestion of organic carbon occurs, which is reflected by the low BOD removal, typically 20% to 30%.

To understand what happens to each component in the influent, we make use of a component material balance which assumes a completely mixed tank (in view of the large circulation flow, F, in comparison to effluent flow, F_1)

$$\text{Input} = \text{output} + \text{accumulation} + \text{reaction}$$

$$X_{0j} F_0 = X_{1j} F_1 + \frac{d(X_j V)}{dt} + V\, D(X_j) \tag{1}$$

where F_0 and F_1 are the flow rates of the inlet and effluent in units of volume per unit of time, X_{oj}, X_{1j} and X_j are concentrations of the component j, in the inlet, effluent and septic tank, respectively, in units of mass per unit volume. V is the liquid volume in the tank and circulating loop. $D(X_j)$ is the specific rate of reaction of component j in units of mass per unit volume per unit time. While the nature of this expression is generally unknown, it is to be determined from kinetic studies and is expected to be a function at least of the concentration of X_j if not other X_i's and temperature.

For the purpose of illustrating some major properties of the system, a few simplifying assumptions will be made which are reasonable. First, let the liquid volume, V, in the system be constant -- while this is not true instantaneously, on the average it has to be so. Second, since the major component in the inlet and effluent is water, the density is taken as constant so that $F_0 = F_1$.

Under these assumptions, the effluent concentrations, X_{1j}, and the bulk concentration in the septic tank, X_j, (and in the circulating loop) are related by the membrane fraction rejection, R_j, for component j, which is a parameter of a given membrane.

$$X_{1j} = (1 - R_j)\, X_j \tag{2}$$

With these assumptions, equation (1) can be simplified to give

$$X_{0j} = (1 - R_j)\, X_j + \frac{V}{F_0} \frac{dX_j}{dt} + \frac{V}{F_0}\, D(X_j) \tag{3}$$

There are several cases of interest:

Case I. No reaction for component j. This would be the case of a component such as sodium chloride. Now Equation (3) becomes

$$X_{0j} = (1 - R_j)\, X_j + \frac{V}{F_0} \frac{dX_j}{dt} \tag{4}$$

The time constant τ_j is obtained by inspection from the above differential equation.

$$\tau_j = \frac{V}{F_0\,(1 - R_j)} \tag{5}$$

Note that in the limit $R_j = 0$, there is no rejection of component j ; the time constant is the normal residence time of a stirred tank. On the other hand, as R_j approaches one, the time constant becomes arbitrarily large, indicating that it takes longer for the system to come to a steady state for a high rejecting component than for a low rejecting component. When the system reaches steady state, Eq. (4) gives the concentration of component j in the septic tank as

$$(X_j)_{ss} = \frac{X_{0j}}{(1-R_j)} \tag{6}$$

This is an important equation because it points out that as rejection, R_j, for component j is increased, the concentration at steady-state in the septic tank increases above the inlet concentration by a factor of $\frac{1}{1-R_j}$. For example, a given membrane may have a chloride of rejection of 0.5 and a phosphate rejection of 0.95. As a result, a steady state concentration in a septic tank will be two times the inlet concentration of chloride, and twenty times the phosphate. Combining Equations (2) and (6), it is clear that at steady state for a non-reacting component the inlet concentration is equal to the outlet concentration.

Case II. Reaction for component i. This would be the case for any organic carbon compound or the organic compounds taken as a whole and represented by their equivalent biological oxygen demand (BOD). Another example of this case would be the nitrate ion which passes through the membrane but also reacts in the anaerobic environment to form nitrogen.

While Eq. 3 gives transient behavior of component i, the steady state equation can be rearranged to give the specific rate of reaction

$$D\,(X_i)_{ss} = \frac{F_0}{V}\,[X_{0i} - X_i\,(1 - R_i)] \tag{7}$$

As a first approximation, $D(X_i)$ is generally a monotonic function of X_i, at least in dilute solution, and for a given input and F_0/V it increases with R_i.

In fact for the simple case of a first-order kinetic reaction, such that

$$\dot{D}(X_i) = k_i\,X_i \tag{8}$$

where k_i is the kinetic rate constant, it can be shown that $(X_i)_1 \geq (X_i)_2 \geq (X_i)_3$ where the subscripts 1, 2, and 3 refer to the cases of $R = 1$, $0 \leq R \leq 1$, and $R = 0$, respectively. The significant point here is that as the membrane rejection for species j increases from zero to one, the steady state concentration of i in the septic tank increases. With the first-order reaction of Eq. (8) the time constant for component j from Eq. (3) becomes

$$\tau_i = \frac{\frac{V}{F_0}}{\left[(1 - R_j) + \frac{V}{F_0}\,k\right]} \tag{9}$$

which shows that it depends on both the rejection and the rate constant.

By using the concentration shown in Table 3 as representative of steady state data, the fraction rejection, the specific rate of reaction, the first-order rate constants, and the time constants for each component are calculated according to the above analysis in Table 4. Also shown are the time constants

Table 4. PARAMETERS CALCULATED FROM COMPONENT MATERIAL BALANCES FOR SEPTIC TANK - MEMBRANE SYSTEM

Component	Average Membrane Fraction Rejection R_j (2)	Parameter Estimates with No Reaction: Steady-State Concentration in Septic Tank $(X_j)_{ss}$ (6) mg/l	Parameter Estimates with No Reaction: Time Constant τ_j (5) days	Steady-State Concentration in Septic Tank $(X_j)_{ss}$ (Table 3) mg/l day	Specific Rate of Reaction $D(X_i)$ (7) mg/l day	Kinetic Rate Constant k_j (8) day^{-1}	Time Constant τ_j (9) days
B.O.D.	0.79	1286	47.6	140	24.1	0.172	5.18
Nitrate Nitrogen	0.60	8.75	25.0	2.2	0.261	0.119	6.28
Phosphate	0.77	143	43.5	87	1.30	0.0149	26.3

Note: Numbers in parentheses indicate equation used to calculate parameter, and $\frac{V}{F}$ is taken as 10.

and the steady-state concentrations in the septic tank if no chemical reaction occurred.

The use of the first-order rate constant k_j in Table 4 is understood to be used just in order to give a reasonable estimate of the time constant for each species. In no way have we proved that the reactions are first-order. With a reasonable knowledge of the time constant, we can assume that in about three time constants the system comes to steady-state for that component if the input is reasonably steady. So, for example, in fifteen to twenty days the system comes to steady state for BOD and nitrate.

The specific rate of reaction for the organic components measured as BOD is 24.1 mg/l day. This is much higher than expected in a normal septic tank. For example, for the same $V/F = 10$, and say, 25% BOD reduction between influent and effluent, the specific rate of reaction would only be 6.75 mg/l day. By holding all but the simplest organic compounds in the system with the membrane as well as the microorganisms, the anaerobic reactions are carried to completion.

Another indication of this activity is from the gas evolved per day from the septic tank. Over a six-week period the gas produced averaged 2.98 liters/day. From the average percent volatile matter in the influent, an expected gas production of 2.6 liters/day is estimated, assuming complete digestion.

Although an anaerobic digestion can go "sour" as a result of a drop of pH caused by a sudden load change, this sytem was remarkably stable as shown by the fact that the pH in the septic tank never went out of the range of 6.5 to 7.2 in over a year of operation. During that time, the system would idle for up to fourteen days, and at other times would be loaded with as much as twenty liters of influent per day.

Because the circulating flow is returned to the first stage in the septic tank, the system is well mixed, and as a result no scum layer forms at the top of the liquid. When the pump is turned off, the majority of the suspended solids settled quickly, leaving only the fine colloidal matter in suspension.

The initial sludge added to the tank was 19 liters from the Hanover sewage plant anaerobic digestor. After 6800 liters of effluent had passed through the system in over eighteen months of experimentation, the sludge volume was about 20 liters. While it appeared to be more dense at the end than it was initially, the significant point is that in this system the volume of sludge that accumulates is less than expected in a normal septic tank.

Without reaction, the nitrate nitrogen would be expected to be 8.75 mg/l from Table 4. Since nitrate (as well as nitrite) nitrogen is reduced in an anaerobic digestion to nitrogen, only about 25% of the inlet nitrate leaves in the effluent. If more nitrate removal is desired, the rejection could be increased by selecting a less porous membrane. In turn, this would increase the steady-state concentration of nitrate in the tank, increase the time constants, and increase the specific rate of reaction. The final selection of membrane porosity is dependent on the final effluent requirements that are imposed on the system.

In the case of phosphate, it was surprising to see that it had an implied specific rate of reaction of 1.3 mg/l day, since no reaction was expected. Clearly, the phosphate level in the tank is less than 143 mg/l as predicted with no reaction. However, when one considers that calcium phosphates salts have limited solubility, it is quite possible that phosphate is being precipitated in the system. For example, the most soluble calcium salt is $CaH_4(PO_4)_2\ H_2O$ at 200 mg/l at 25°C, which is equivalent to 110 mg/l of PO_4.

It was not determined where the insoluble phosphate has gone. While the obvious place to look for it is as a precipitate on the membrane surface, the membrane surface showed no permanent inorganic deposits. As a result, the precipitate most probably is accumulating in the sludge layer. In future work, the fate of phosphate should be determined -- especially to assure that it does not interfere with the long-term operation of the system and the ultimate sludge disposal.

From Table 3 it is clear that the level of phosphate in the effluent is significantly reduced as the membrane rejection is increased.

CONCLUSIONS

It has been demonstrated that the concept of using a septic tank - membrane system is feasible for the treatment of domestic waste water. In fact, several key technical advances, which are essential for the development of this concept into a practical design, are the following:

1. The cyclic operating procedure results in a long-term steady-state flux because of its inherent hydrodynamic cleaning action. In this way, membrane fouling caused by suspended solids can be overcome without specific mechanical or chemical cleaning steps.
2. Depending on the operating cycle, the bulk velocity of the fluid over the membrane surface can be in the range of 0.5 to 4 ft/sec which is in contrast to 12 or more ft/sec recommended for continuous operation of membrane modules which process suspended solids.
3. Practical flux levels in the range of 10 to 15 gfd were achieved with a flat sheet membrane module for over 900 pump hours or 1500 hours of real time. No membrane module has ever been reported to have operated at this level of flux for such an extended time period for any kind of sewage or waste water without frequent cleaning of the membrane.
4. The water quality of the treated effluent is similar, if not better, than secondary treatment. For example, E[1] coli and turbidity are zero, while the reduction of BOD by 85 to 95% is possible. A particular feature of this system is nitrate reduction by about 75%.

5. The anaerobic rate of digestion of organic carbon in the septic tank is enhanced by a factor of 3 to 4 because of the increased concentration of microorganisms and substrate caused by the membrane. The pH stability of the digester is excellent, even with intermettent loading. The sludge accumulation is less than in an ordinary septic tank.

Before recommending further work, it is useful to ask if the concept will ever be economical. It is possible to make such an evaluation based on the following conservative development:

We require to treat 300 gal/day with a 2:1 cycle and bulk velocity 4 ft/sec with a membrane module having a steady-state flux of 7 gfd. Let's use a commercial spiral wound module of 20 ft^2 at a cost of $130. The estimated installed cost of a 1000 gallon septic tank with 4 modules, pump, piping and electrical work is $2200. The upper limit on the annual operating cost for electricity at 5¢/kwh, maintenance, and annual membrane replacement is $580. For a two-year membrane life, the annual cost decreases to $320.

While this is more than a septic tank and leach field installation, it is a reasonable cost for a home owner when the normal septic tank system is not permitted or is not working properly.

Since the results are encouraging and the estimated cost is within reason, further work is recommended in developing this septic tank membrane system. In particular, the following questions need to be investigated.

1. How reproducible are the results?
2. What is the best commercially available module design for this service?
3. What is the maximum service life of a module?
4. What is the reliability of the system?

5. What safety features are needed to protect against membrane failure?

6. What is the phosphate removal mechanism?

7. What is the energy requirement for the system?

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