Virus removal by advanced membrane filtration for wastewater reclamation

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ABSTRACT: Measurements of indigenous and seeded male-specific (MS2) bacteriophages were made in an effort to gain insight into the response of membrane filtration systems to varying virus concentrations and varying flow rates at the Terminal Island Treatment Plant, operated by the City of Los Angeles Bureau of Sanitation. Bacteriophages were seeded into secondary effluent that had been filtered through a trimedia filter. The seeded effluent was then processed by microfiltration (MF) and reverse osmosis (RO) pilot units for which the Department of Water and Power was evaluating effluent water quality parameters in conjunction with a water reclamation project. The samples were assayed for virus. The seeded tests utilized higher concentrations of MS2 viruses and sampled the process streams with higher time resolution than those used by other researchers in comparable experiments. As expected from the physics of RO process, the RO unit reduced the virus concentration below the threshold of detection, but the MF membranes consistently reduced virus concentrations by less than one log unit (order of magnitude). This MF performance differs from most results of similar tests carried out elsewhere, but it was consistently observed, despite substantial variability in the virus removal factor, as revealed by the high time resolution of the measurements. Budgetary limits prevented extending this research to clarify the indications in the data that removal efficiency may be affected by the MF unit's backwash cycle, or the membrane flux, but if these results can be verified, they may provide valuable insight for improved membrane technology and planning for large-scale membrane-based water reclamation. *Water Environ. Res.*, **70,** 1198 (1998).

KEYWORDS: reclamation, membrane filtration, microfiltration, reverse osmosis, virus, bacteriophage, removal efficiency

Introduction

Human enteric viruses are highly resistant to water treatment and disinfection methods because they have evolved to survive passage through the highly acidic stomach to infect the small intestine or enter the blood stream there. Thus, it is important in planning for wastewater reclamation to verify that enteric viruses are removed or inactivated (Grabow, 1993).

In March and April 1996, the Los Angeles, California, Bureau of Sanitation (BOS) Research Group tested the effectiveness of microfiltration (MF) and reverse osmosis (RO) in removing viruses from reclaimed wastewater at the Department of Water and Power (DWP) Pilot Facility at Terminal Island Treatment Plant (TITP), which had been set up so that the DWP could evaluate effluent quality resulting from membrane filtration. This was a step towards implementing the City's timetable for reclaiming increasing percentages of its wastewater in coming decades. Seeding with bacteriophages with characteristics similar to those of enteric viruses allowed the study to be conducted with higher time resolution than many other reported tests of membrane filtration and allowed filter performance to be evaluated using new criteria. As microbiological studies are highly vulnerable to contamination and other forms of distortion, procedures to maintain the data quality were followed as described in the Experimental Procedure section. This paper describes the tests and their results.

This study was focused primarily on the MF unit, for two reasons. First, the tests conducted were believed to represent one of the most extreme virus challenges to MF performed to date, whereas there has been previous significant experience with use of RO to remove viruses. Because during the first two days of testing RO conformed to past experience by persistently removing the viruses below the threshold of detection, additional testing of the RO effluent was considered a poor use of limited laboratory resources. Second, MF is also planned for use as a pretreatment for other forms of disinfection, such as ultraviolet (UV) (Jolis and Hirano, 1993), so that understanding MF performance is more critical for future planning than RO performance.

Other technologies in addition to MF and RO will likely become important in the future. Ultrafiltration and nanofiltration are membrane technologies with pore sizes intermediate between MF and RO (Dwyer *et al.*, 1995). Trimedia filtration (TMF) and UV disinfection technologies are currently more widely used than membrane filtration. A key task for the near term is to determine the best way to combine the various filtration and disinfection technologies to produce reclaimed wastewater that is both economical and safe for a wide range of beneficial uses.

Using Seeded Bacteriophages

Use of seeded male-specific (MS2) bacteriophages is preferred to observing the indigenous enteric viruses (IAWPRC, 1991), because the phages are nonpathogenic to humans but have a resistance to some forms of disinfection and filtering that is similar to the resistance of many enteric viruses, and they are easy to count by their effect on *Escherichia coli* cultures. The International Organization for Standardization has developed standardized techniques for detecting phages in water as indicators of water quality (Grabow, 1993) and even more recently, in 1995 the California Department of Health Services (DHS) has approved phage testing as a substitute for enteric virus testing, so this is an innovative aspect of this study. However, by the time of the approval substantial previous experience had been accumulated by researchers who used MS2 phages as tracers in other types of tests. In one study, Yahya *et al.* (1996) compared MS2 and polio viruses for sensitivity to inactivation by UV and found that poliovirus is more sensitive to UV than is MS2 because 4 log units of inactivation were obtained for poliovirus at a UV dosage of 80 mWs/cm^2, while 120 mWs/cm^2 were needed for MS2. On the other hand, Yahya *et al.* (1991) had previously found that MS2 was much more sensitive

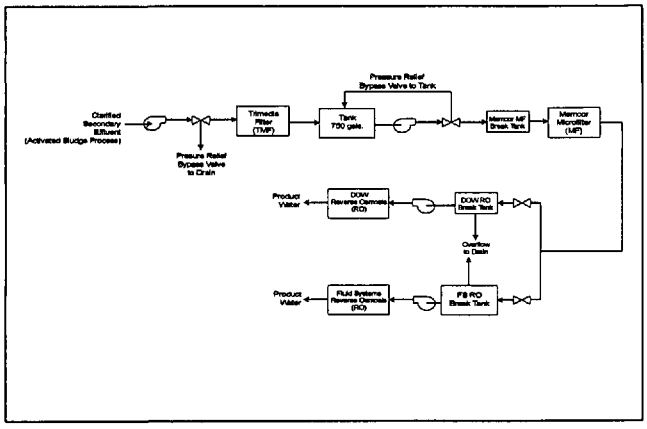

Figure 1—Schematic of DWP filtration-reverse osmosis (MF/RO) pilot unit at TITP.

than poliovirus to ions leached from copper and galvanized pipes. Yahya *et al.* (1993) and Powelson et al. (1993) used MS2 and PRD1 bacteriophages, respectively, as tracers in tests of virus removal by slow sand filtration and nanofiltration and tests of virus removal in aquifers being recharged with reclaimed wastewater. As PRD-1 phages are larger than MS2 phages (65 nm versus 28 nm), they were removed to a greater extent in these tests. At present, MS2 seems more suitable for such mechanical filtration tests than for tests of disinfection by chemicals or UV. The results of mechanical filtration are easily extrapolated to other viruses of known sizes without being influenced by factors that affect sensitivity to chemicals or UV.

The MS2 phages are typically present in wastewater in concentrations comparable to those of human enteric viruses, but both types are removed by standard wastewater treatment processes at approximately the same rate (Havelaar, 1993). Thus, the background concentration of MS2 phages in the secondary effluent, which was used as the feed to MF pilot units (Willinghan *et al.,* 1992) was relatively low, often in the range of 10 to 100 viruses per 100 mL. Moreover, a high concentration of coliform bacteria and temperatures higher than 30°C seem to be necessary for significant multiplication of MS2 phages under natural conditions (Havelaar, 1993). Thus, tracer tests that seed a wastewater stream with a significantly higher concentration of viruses provide confidence that the numbers of viruses observed after filtration are indicators of filtration effectiveness.

Other tests of MF units (Water Board, Sydney-Illawarra-Blue Mountains, 1992, and Willinghan *et al.,* 1992) have observed the filtration efficiency for indigenous MS2 phages. However, they have taken samples no more frequently than once a day, except for the Australians' intensive sampling runs, each of which took samples every five minutes for an hour. The need to use a higher concentration in a seeded test and the limited supplies of concentrated virus culture dictated the use of much briefer laboratory tests, with sampling conducted every few minutes.

Experimental Setup

Figure 1 is a simplified schematic of the experimental facility, showing only the equipment that was used in the virus testing. The other MF and RO units and much of the auxiliary equipment that was used in the DWP testing program are omitted. The TMF consists of three trimedia pressure filters, each with anthracite on the top, sand in the middle, and garnet on the bottom.

The Fluid Systems, Inc. (San Diego, California) RO unit used thin film composite (TFC) (polyamide) membranes (model TFCL 4820 HR), which cannot tolerate free chlorine. The Fluid Systems RO system consisted of a 4-vessel first stage and a 2-vessel second stage. Each vessel contained three cartridges, each with 6.7 m^2 (72 sq ft) of membrane, for a total surface area of 120.3 m^2 (1 296 sq ft). The Dow Chemical Company RO system used TFC membranes (Model BW30-4040 Filmtec [Dow Chemical Company, Midland, Michigan]), which are coated with a polymer for biofouling resistance and are intolerant to free chlorine. The Dow RO system also consisted of a 4/2 two-stage system. Each vessel contained three cartridges, each providing 7.4 (80 sq ft) of membrane area, for a total surface area of 133.8 m^2 (1 440 sq ft). Because the RO units operated continuously during the tests without interruption for treatment of fouling, their operations are not discussed further.

By contrast the operation of the Memcor MF unit (model 3M10C, Memtec America Corp., Timonium, Maryland) was more complex. The Memcor MF consisted of three parallel, hollow fiber, polypropylene membrane cartridges, with a 310-μm lumen diameter and a 0.2-μm nominal pore size in the membrane covering the outside of each fiber. Each cartridge had enough fibers for a total surface area of 15 m^2. The membrane formation process was evidently well controlled, because the vast majority of the pores were very close to the nominal size of 0.2 μm. Although the upper limit for the size of a pore is 0.35 μm, 95.5% of the pores were in the range 0.195 to 0.205 μm, and 99.5% ranged from 0.185 to 0.210 μm. This provided a relatively steep cutoff in the sizes of particles that were mechanically filtered out.

The MF modules were used in dead-end or direct filtration mode, which is the only one used in Memcor microfiltration units, and probably was chosen to maximize recovery of water from the influent. As this equipment has been used primarily for filtration of fresh water for drinking and for other purposes in which there is much less material to filter out than in wastewater reclamation applications, this configuration would have been the obvious choice. The water flows from outside of each fiber through the membrane into the lumen. Every few minutes there is a backwashing cycle in which compressed air at 700 kPa (100 psi) is used to blow the collected solids outward into water that is then discarded into the in-plant sewer. Thus, although these systems are called continuous microfiltration (CMF) units by the manufacturer, they actually do not operate completely continuously in the manner of the RO units, but alternate between normal operation and the backwash cycles. In these tests the backwash cycles lasted approximately 2 minutes and began after every 18 minutes in normal filtration mode.

At much longer intervals, a week or more, chemical cleaning cycles remove built-up biological material (Memtec America Corp., 1995). From late September 1995 to late February 1996, as recommended by Memcor, the transmembrane pressure (TMP) in the MF modules during normal operation after the membranes had been chemically cleaned with a mixture of hydrogen peroxide, sodium hydroxide, and surfactants, with no free chlorine was 34 to 55 kPa (5 to 8 psi) for a flow rate of 68 to 76 L/min(18 to 20 gpm). The maximum pressure before

Table 1—Summary of experimental parameters in pilot tests.

Date	Start time	Stop time	TMF effluent, L (gal)	Flow rate, L/min (gpm)	Membrane flux, $L/m^2 \cdot min$ (gpm/m^2)	Seeded viruses in TMF effluent	Sample			
							Type	Location	Frequency	
									Total no.	After backwash
03/27	0 815	0 915	2 840 (750)	68–76 (18–20)	1.5–1.67 (0.40–0.44)	01×10^{13}	grab	MF in, MF out, RO out	7	not recorded
04/03	0 730	0 810	2 840 (750)	68–76 (18–20)	1.5–1.67 (0.40–0.44)	01×10^{11}	grab	MF in, MF out, RO out	9	not recorded
04/23	0 930	1 300	11 000 (3 000)	68–76 (18–20)	1.5–1.67 (0.40–0.44)	01×10^{12}	composite	MF in, MF out	13	4
04/29	0 740	0 905	5 700 (1 500)	53–61 (14–16)	1.17–1.32 (0.31–0.35)	02×10^{13}	composite	MF in, MF out	5	1
04/29	0 930	1 040	5 700 (1 500)	76–88 (20–22)	1.67–1.82 (0.44–0.48)	02×10^{13}	composite	MF in, MF out	5	1
04/29	1 100	1 200	5 700 (1 500)	98–100 (26–28)	2.16–2.35 (0.57–0.62)	02×10^{13}	composite	MF in, MF out	5	1

the next chemical cleaning, which was required 150 to 350 hours later, was 103 to 172 kPa (15 to 25 psi) (DWP, 1996).

Experimental Procedure

The virus assays were performed at the Hyperion Treatment Plant by experienced laboratory staff of the microbiology unit in the biology section of the Environmental Monitoring Division (EMD). The assay technique used was the Top Agar Overlay Technique derived from Adams (1959). Although this is an established assay method, it has not been included in *Standard Methods* (APHA *et al.,* 1995). The bacterial strain used in the assay was *E. coli* 15597, and additional details of the procedure follow the practice of the Los Angeles County Sanitation District's San Jose Creek Water Quality Laboratory. All samples were refrigerated at 1 to 4°C immediately after collection and assayed within 3 hours.

The viruses were supplied by BioVir Laboratories, Inc. (Benicia, California), a laboratory certified by the state of California. They routinely use several methods to ensure the integrity of the cultures that they supply. Their cultures are obtained from the American Type Culture Collection (Rockville, Maryland) and are checked for host specificity and for inactivation by ribonuclease. Viruses are then cultured in host organisms to desired concentrations for customers.

Because the study assessed the MF's contribution as a system component to meeting a regulatory virus-removal standard, only the influent and the filtrate were assayed for viruses. The vast majority of the removed viruses would be expected to be in the backwash, because the only other place the viruses could go would be into the filter membrane and support material. This observation implies that the determination of virus fate would be more thorough if the virus content of the backwash is compared to that of influent in the filtrate. However, this comparison is not a simple task, and cases in which it was done are not known. These comparisons were not made during the virus removal studies in, for example, the Blackheath, Australia, study (Water Board, 1992) or the Baltimore study (Willinghan *et al.,* 1992).

Before the seeded virus tests were conducted, preliminary experiments measured the concentrations of indigenous MS2 phages at several points: the TMF inlet and outlet, the MF outlet, and the RO outlets. These measurements were made once on each of six days: March 12th, 13th, 14th, 19th, 20th, and 21st. Also on March 19th, several parameters of the permeate from two RO units, including the result of a search for enteric viruses, were recorded.

Table 1 summarizes parameters of the experimental runs from March 27 to April 29, 1996. As the previous tests had shown that the virus levels in the mixing tanks and MF inlet were not significantly different and that virus removal by reverse osmosis was below the threshold of detection within available measurement capabilities, samples were taken only at the MF inlet and MF outlet on April 23rd and 29th. Also, to reduce the total number of samples that the laboratory had to process and to provide a more comprehensive monitoring of virus levels than would be provided by single samples taken at widely spaced times, composite samples were taken on those days. Each analyzed sample was composited from two or three samples taken over an interval of 3 to 6 minutes at one of the two sampling points. Corresponding samples were taken at each time at each sampling point. The measurements taken during periods of normal MF operation were separated from those taken immediately after a backwash. On April 29th, the period between the backwashes was adjusted to match the flow rate to maintain the same schedule of backwashes after filtering every 1 320 to 1 510 L (350 to 400 gal) as in the previous tests.

As each of these tests lasted at most 4 hours, the degree of fouling of the membrane did not change significantly during the test. Thus, the TMP was nearly the same before and after each test. Because the April 29th test was conducted soon after a chemical cleaning, only 70 and 90 kPa (10 and 13 psi) were needed to achieve respective flow rates of approximately 76 and 106 L/min (20 and 28 gpm).

To assure the quality of the laboratory procedures, three forms of checking were done. On some days a few samples were taken before any seeding to check if there had been any replication of the viruses from previous experiments. The virus concentration supplied by BioVir Laboratories was checked on

Table 2—Water quality parameters of TMF effluent (August to December 1995).

Parameter	Average ± standard deviation	Minimum	Maximum
BOD5 (mg/L)	1.16 ± 1.2	nondetectable	2.80
SS (mg/L)	0.51 ± 0.43	nondetectable	1.12
Oil and grease (mg/L)	0.4 ± 0.58	nondetectable	1.10
Cl2 residual (mg/L)	nondetectable	nondetectable	nondetectable
DO (mg/L)	6.32 ± 0.35	6.00	6.90
TOC (mg/L)	7.96 ± 0.44	7.27	8.54
Turbidity (NTU)	0.65 ± 0.36	0.45	1.30
pH	7.37 ± 0.10	7.27	7.53

April 23rd and 29th by titration. On March 27th and April 3rd, samples were taken both at the mixing tank and at the inlet of the microfilter to check whether anything caused a significant loss of viruses between the mixing tank and the MF inlet. This was necessary to verify that any virus reduction between the inlet and the outlet could be attributed to the MF and not to any other virus-killing influence in the water.

Observations and Analyses

Table 2 shows that even without microfiltration the quality of TMF effluent is quite good. This table selects key parameters and summarizes quality measurements made from August to December 1995, when the measurements were discontinued because the values were negligible or satisfactorily stable. In addition, there were no detectable quantities of more than 100 commonly measured organic chemicals, including both volatile and nonvolatile compounds, many pesticides, and herbicides (DWP, 1996).

Table 3 shows the results of the quality assurance tests for the laboratory procedures. The average sample concentration at the MF inlet and the tank are in good agreement. The results from titration tests by EMD also agree well with the nominal virus concentrations specified by BioVir Laboratories. Likewise the virus concentrations before seeding were insignificant, implying that little if any virus multiplication occurred in the test apparatus during the period between the tests.

Table 4, part (a) shows the indigenous MS2 phage counts from the samples on March 12th to 21th. Part (b) lists the parameters observed for the permeate from, respectively, the Dow and Fluid Systems RO units, as measured on March 19th. The actual virus counts on March 19th are upper bounds, and are, respectively, less than 1 plaque forming unit (PFU)/190 L for the Dow RO and less than 1 PFU/210 L for the Fluid Systems RO (or approximately 5×10^{-6} PFU/mL).

Figure 2 shows the bacteriophage counts and their times for March 27th, plotted with a logarithmic ordinate to aid assessment of the reduction provided by each type of unit. Note that the abscissa does not show a uniform time increment per unit length, but gives each time separately. The only available MF inlet value is an estimate based on an erroneous dilution, and the time of the sample was lost in the laboratory. It is repeated across the plot for ease in visual comparison with the values recorded at the other sampling points. All but two of the values for the RO output are upper bounds, because no viruses were detected in these samples. Assuming that the MF inlet value is approximately constant, as was the case on April 3rd and 23rd, when the same flow rate was used, March 27th is the only day during which significantly more than 1 log unit of removal was observed.

Figure 3 shows the results from April 3rd using the same format, except that valid values were obtained for the MF inlet. All of the RO values are upper bounds. The MF data for this day not only show much less removal than on March 27th, but the removal efficiency declines relatively steadily in a way that is unique to this day. From the physical nature of reverse osmosis one would expect that as long as the RO membrane is undamaged, it is extremely rare for any virus particle to pass through the membrane. The RO membrane's impermeability is seen not only in the data from March 27 and April 3, but in the indigenous phage data and enteric virus data recorded on

Table 3—Summary of measures for quality control.

	Bio Vir laboratory		Environmental Monitoring Division Laboratory		
	Virus		Virus concentration		
				Sample mean ± standard deviation	
Date	Concentrate quantity (mL)	Nominal concentration (PFU/mL)	Titration measurement (PFU/mL)	Tank (PFU/mL)	MF inlet (PFU/mL)
03/27/96	20	5.0×10^{11}	not done	$(4.55 +/- 0.46) \times 10^{6}$	$(3.50 +/- 0.00) \times 10^{6}$ [a]
04/03/96	2	5.0×10^{10}	not done	$(3.2 +/- 0.34) \times 10^{4}$	$(3.79 +/- 0.78) \times 10^{4}$
04/23/96	100	1.0×10^{10}	9.60E + 09	no samples	$(1.42 +/- 0.44) \times 10^{5}$
04/29/96	100	6.2×10^{11}	4.50×10^{11}	no samples	$(1.70 +/- 0.35) \times 10^{6}$

[a] approximate count.

Table 4—Preliminary indigenous virus counts (03/12–21/96).

Date	TMF input	Memcor MF input	Memcor MF output	Dow RO output	Fluid systems RO output
			a. Bacteriophage (PFU/mL)		
03/12/96	39	16	3	1	—
03/13/96	6	4	0	0	0
03/14/96	7	5	0	0	—
03/19/96	10	13	3	<1.0	<1.0
03/20/96	12	—	1	<1.0	—
03/21/96	22	—	1	<1.0	—
			b. Enteric viruses (PFU/200 L)		
03/19/96	—	—	—	<1.0	<1.0

"—" indicate that the parameter was not measured.

March 12th to 21st. These observations verify the integrity of the RO membrane.

Figure 4 shows the results from April 23rd for the times of normal MF operation and the data recorded during the periods immediately after backwashes. These periods were distinguished in an effort to determine whether the large peak observed on March 27th might be associated with backwashing. The four points marked ABW on this graph, are the results from the samples taken immediately within 90 to 120 seconds after backwashes were completed.

Figure 5 is like Figure 4, showing the data from April 29th, combining normal and post-backwash data. The first four points were recorded at approximately 53 to 61 L/min (14 to16 gpm), the next four at 76 to 83 L/min (20 to 22 gpm) and the last four at 98 to 106 L/min (26 to 28 gpm). Likewise, the three points marked ABW on this graph, are the results from the samples taken immediately within 90 to 120 seconds after backwashes were completed.

The most prominent feature of the April 3rd data is an upward trend in the MF outlet counts. However, the April 23rd and 29th data do not show such a trend but show a relatively stable level with modest fluctuations. The logarithmic plots also show that the percentage fluctuations of the inlet and outlet concentrations are similar in magnitude, although not well correlated in time.

During normal operation of the MF on April 23rd, approximately 0.8 log units of virus reduction occurred, but immediately after backwashing the virus reduction was typically in the range of 0.4 to 0.5 log units. However, in the results from April 29 this difference between normal and post-backwash operations did not persist.

In comparing these results to, for example, the Blackheath, Australia, study (Water Board, 1992), the Baltimore study (Willinghan *et al.*, 1992), and Southern California Metropolitan Water District study (Kostelecky *et al.*, 1995), it is clear that the virus removal in the April 3rd, 23rd, and 29th experiments was much less than the approximately 2 to 3 log units that other experimenters have usually observed. However, the Baltimore study observed one period of four weeks when only 1 log unit of reduction occurred, and this limited reduction also occurred on several other occasions when the experiments lasted only one week. Also, Gagliardo *et al.* (1996) in a much briefer study observed highly variable virus removal in their work with a Memcor microfiltration unit.

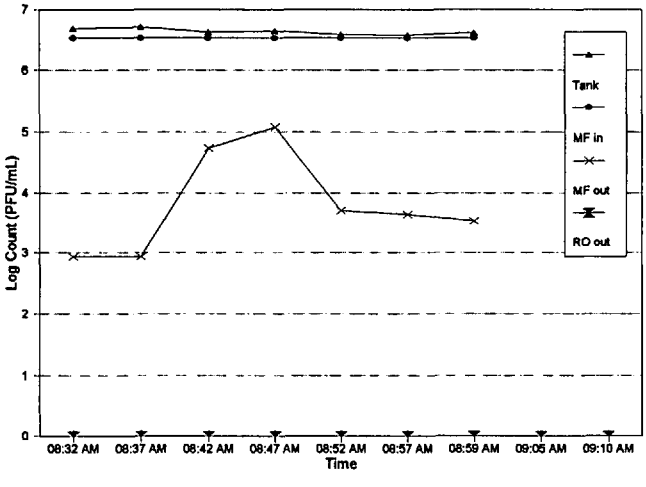

Figure 2—MS2 counts for MF and RO (03/27/96).

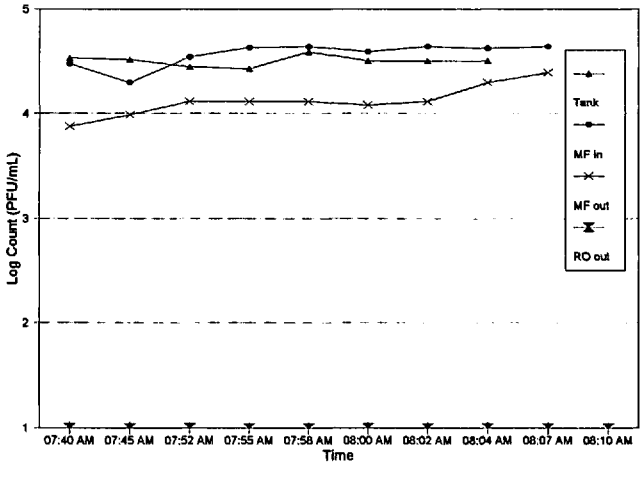

Figure 3—MS2 counts for MF and RO (04/03/96).

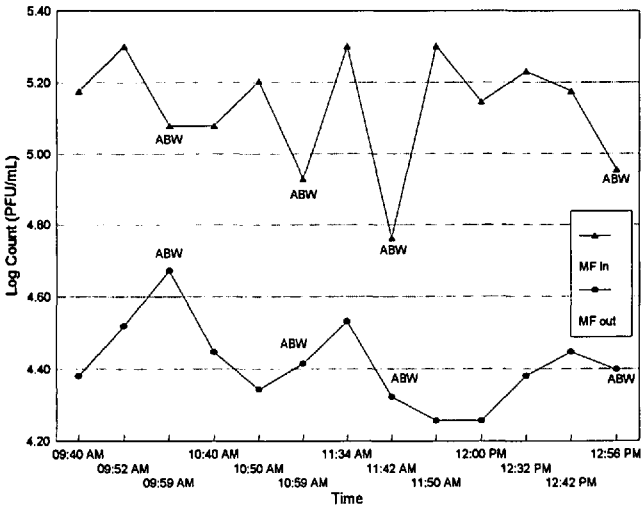

Figure 4—MS2 counts for MF (04/23/96).

The results on April 29th show a trend toward increased virus removal efficiency with increased flow rate during normal operation, but the post-backwash measurements do not show this trend. At 53 L/min (14 gpm) approximately 0.4 log units of virus removal are observed in normal operation; at 83 L/min (22 gpm) approximately 0.6 log units are observed; and at 102 L/min (27 gpm) the factor of reduction is nearly 0.8 log units, with one pair of samples showing a full log unit.

The results for the indigenous viruses in Table 4 are consistent with the results from seeded experiments, showing less than 1 log unit of virus removal by the MF unit. However, the small numbers of the indigenous viruses do not have much statistical significance.

Discussion

Comparing the results from all four days suggests substantial variability from one day to another, and it is not clear now whether the variability resulted from an intrinsic variability in filtration efficiency of the microfiltration unit or was affected by the large variation in the input concentration of viruses. However, because the results for the last three days seem to be relatively stable, the rise in efficiency with flow rate seems to be trustworthy.

An explanation for this rise is not evident. One might expect that a higher flow rate would reduce the efficiency of virus trapping in a filter medium with a pore size much larger than the size of a virus particle. The explanation presumably lies in an interaction with the other material being filtered from the wastewater stream, but further study would be needed to clarify the details.

Some perspective on the many fluctuations in the data can be provided by a more careful assessment of their uncertainty. Typically, evaluation of the mean and standard deviation are used to estimate the uncertainty of a given set of points that are members of the same population group This is what was done above to show that the observed counts for the mixing tank on March 27th were not significantly different from the count predicted by the dilution calculation.

A few additional comments about virus fates also seem appropriate. Ordinarily a number balance for the living organisms comparable to mass balances in other fields, for example, fluid mechanics, cannot be established. However, because the virus assays measure virus concentrations in plaque forming units per unit volume, an analog of a mass balance might be developed here because the time of these measurements is too short for significant virus replication to occur, even if conditions were favorable and the apparatus contains nothing that would cause significant virus inactivation. To obtain a total count, the concentration would be multiplied by a total volume in a given time. Then corresponding concentration and volume estimates would have to be made for the backwash. Obtaining these estimates would require some process to separate the viruses from the other material in the backwash. As noted in the quality control section, experiments that have attempted to determine virus fates in this way are not known.

Still another question is the nature of the virus-trapping mechanism in microfiltration, because free viruses are much smaller than the pores of the filter medium. A peer reviewer of this manuscript has suggested that locally charged regions on the virus surface may be attracted to charges on the molecules of the filter medium or that many of the plaque forming units are fragments of *E. coli* membrane with viruses bound to them instead of free virus particles and, hence, are closer to the pore size. The first of these suggestions might be tested by putting a seeded solution into an electrodialysis unit and comparing the virus concentrations in the salt-concentrating and salt-depleting chambers after a current has been applied. The second might be tested by performing electrophoresis or radian centrifugation on a sample of virus concentrate and assessing the biological activity of fractions with differing mobility or sedimentation rate.

Conclusions

A pilot study of virus removal by microfiltration and reverse osmosis yielded the following results:

- The stable virus removal efficiency achieved with microfiltration was less than 1 log unit, which was unexpectedly low compared to most other MF studies, but consistent with the results during several periods in the Baltimore study (Willinghan *et al.*, 1992);

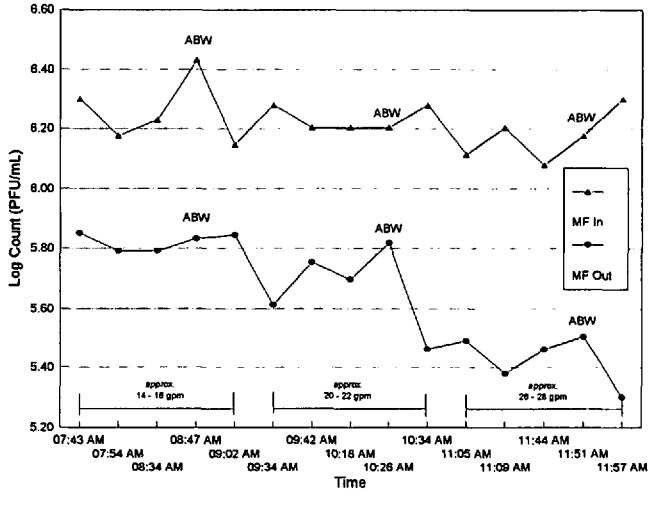

Figure 5—MS2 counts for MF (04/29/96), varying flow rates.

- Virus removal efficiency in the MF appeared to increase modestly with the flow rate but was not systematically different between periods of normal operation and the aftermaths of backwashes;

  As expected, virus removal by reverse osmosis reduced the concentrations below the threshold of detection.

These results imply that in a full-scale MF/RO system the virus removal efficiency of the MF unit is not important for complying Title 22 standards (State of California, 1978) for viruses. Also, a full-scale MF/UV system should be designed so that the UV component can meet Title 22 standards for viruses by itself, unless the reasons for the varying effectiveness of MF virus removal become clear enough to be used in planning and design.

It would be beneficial to conduct an additional investigation to clarify the reasons for occasional low virus removal efficiency by microfiltration. As this additional investigation may be costly because of the high loading of virus seeding and the high time resolution of sampling that would be required, the study may best be undertaken by several municipalities in cooperation or by a state or national agency concerned with public health or environmental protection. More remains to be learned about the virus removal efficiency that can be expected from advanced membrane filtration units.

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