DE filtration to remove Cryptosporidium

DE filtration is far more effective than conventional or direct granular media filtration in reducing concentrations of Cryptosporidium oocysts.

Jerry E. Ongerth
and P.E. Hutton

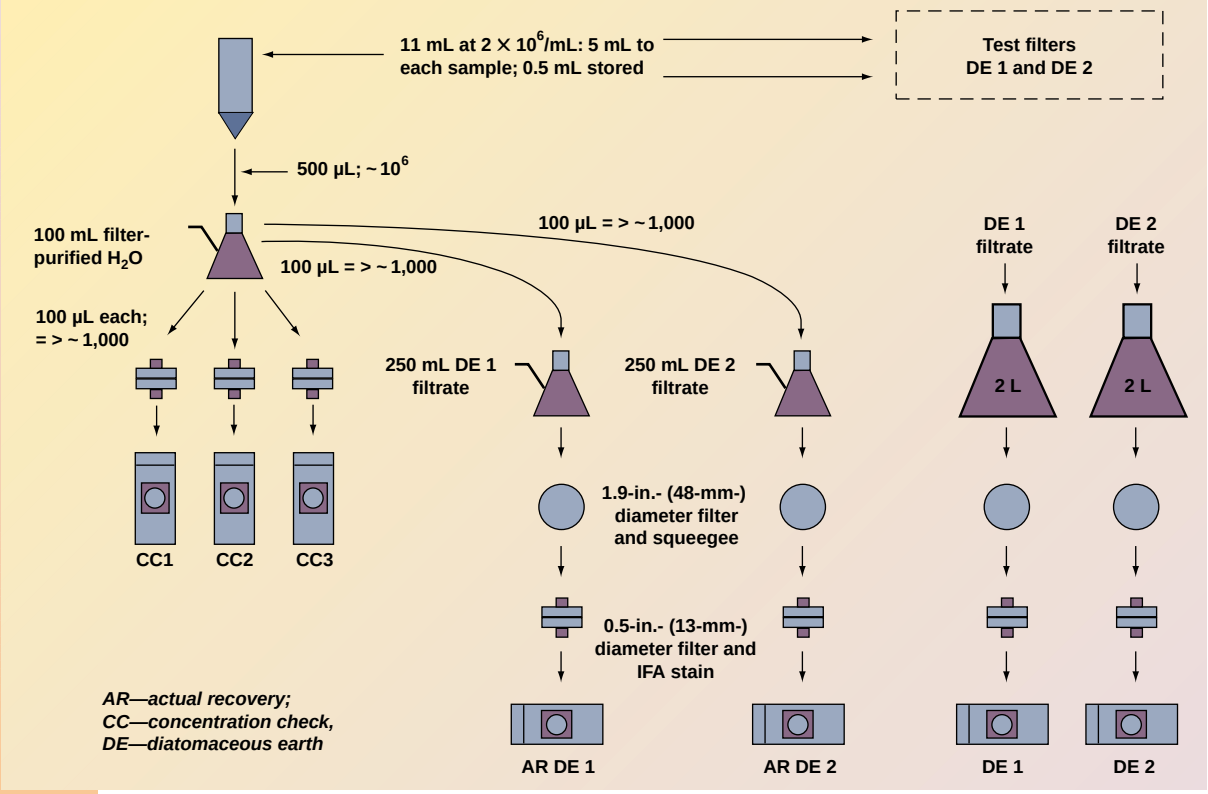
Laboratory-scale testing investigated the degree of *Cryptosporidium* oocyst reduction provided by diatomaceous earth (DE) filtration. Three grades of DE from two manufacturers were used in the tests. Reduction was measured using seeded river water applied to Walton test filters. Tests were run for filtration rates of 1 and 2 gpm/sq ft (2.4 and 4.9 m/h). Each run was replicated three times, and quality control was rigorous. Approximately 6 logs of reduction in the concentration of *Cryptosporidium* oocysts can be expected under routine operating conditions using DE grades having permeability of <1.2 Darcy. Log reductions varied predictably according to the permeability of the DE grade and the filtration rate; they were significantly higher at the higher filtration rate. Agreement was excellent between runs, enabling researchers to distinguish with consistent statistical significance the differences in performance.

Filtration of surface water using granular media is important in controlling the cyst-forming protozoan parasites *Cryptosporidium* and *Giardia*, which resist common disinfection practices.[1,2] These organisms are present in virtually all surface water at concentrations that require some control for assurance of public health protection.[3–6]

Cryptosporidium oocysts and *Giardia* cysts both have negative surface charges similar to those of typical naturally occurring particles in surface water. This suggests they would behave like other natural particles of similar sizes in conventional water treatment processes.[4,7] Both test- and full-scale granular media filters are capable of 2–4-log removal for both *Cryptosporidium* and *Giardia*, depending on water quality and operating conditions.[1,2,8]

In diatomaceous earth (DE) filtration, particles are trapped in a rigid matrix. Essential features that determine performance are well established and include diatomite grade, precoat rate, bodyfeed rate,

FIGURE 1 Schematic diagram of test filter seeding for Cryptosporidium log reduction measurement



and filtration rate. Testing for *Giardia* cyst removal suggests that DE filtration is practical and depends only on particle characteristics including size, shape, concentration, and, to some extent, surface charge.

Previously published studies about the behavior of *Cryptosporidium* oocysts and *Giardia* cysts in conventional water treatment processes (including DE filtration) have helped to establish the following approaches to testing as well as specific testing conditions needed to plan and carry out successful performance evaluations.

- Analytical procedures must be quantitative. To achieve that, a procedure must include routine measurement of recovery efficiency for each medium to be tested (i.e., for raw water [independent measurements for each type and turbidity], for raw water with chemicals, and for filtered water).
- Seeding concentrations must be consistent with the measured background concentration in the water and the capabilities of the analytical method.
- Concentrations in the seeded medium must be measured and must include appropriate measurement of recovery efficiency in the seeded medium. Values calculated from feed concentrations and flow rates are used to estimate required seed quantities and to compare against measured concentrations.
- Performance evaluations based on continuously seeded treatment systems offer a major advantage by eliminating the need for assumptions regarding the effects of mixing and dispersion required by slug-fed testing.

Objectives

The objectives of this project were to measure the log removal of *Cryptosporidium* oocysts that DE filtration provided, develop definitive data about the effectiveness of DE filtration for removing *Cryptosporidium* from raw water, and provide a basis for planning focused, large-

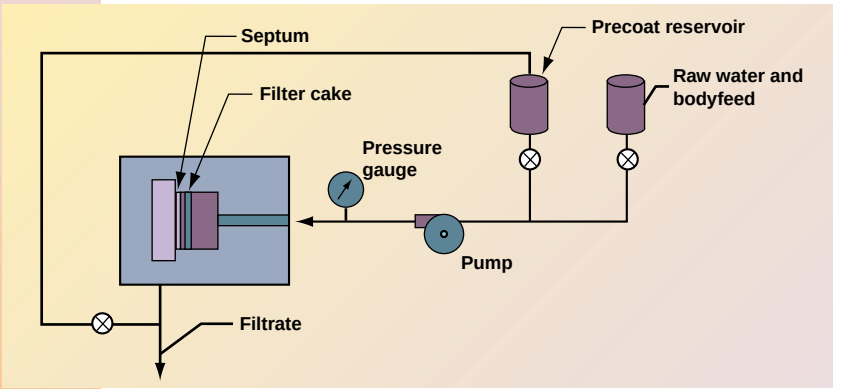
TABLE 1 Summary of DE product characteristics* used in test filters for measurement of Cryptosporidium oocyst removal

DE Grade	Median Size—*µm*	Median Pore Size—*µm*	Uniformity Coefficient	Permeability *Darcys*
A1	16.4	5.0	5.5	0.53
B1	18			0.5
A2	22.3	7.0	4.7	1.2
B2	24			1.0
A3	34.3	13.0	5.0	3.1
B3	42			3.75

*Typical data reported by manufacturers

scale testing dependent on the quality of treatment identified in laboratory tests. The purpose was to provide information a municipality and its engineering consultants would need before they decide to test or use DE filtration in their utility.

FIGURE 2 Schematic diagram of a Walton filter used for measuring Cryptosporidium oocyst removal by DE filtration



Approach

Bench-scale testing was the first step in determining the overall applicability of DE filtration to the control of *Cryptosporidium* oocysts in surface water. Contingent on the findings of this study, a logical second step would be to proceed with pilot-scale testing to establish performance characteristics to enable preliminary engineering comparisons. The approach consisted of three elements.

- Bench-scale studies defined the basic characteristics of DE filtration as a function of two key operating parameters: DE grade and filtration rate. A single low-turbidity (~1 ntu) natural surface water was used for all testing. The effect of the filtration rate was determined for selected grades of DE appropriate for use in water filtration. Comparable grades of DE from different suppliers were tested to establish relative performance for identical operating conditions. Precoat and bodyfeed conditions were examined in preliminary studies to determine effective rates for water treatment.
- *Cryptosporidium* oocysts were seeded continuously during testing periods. Unpreserved fresh organisms produced approximately monthly were used for all seeding studies. Performance was measured during periods of continuous seeding. Counting to establish seed concentrations was confirmed by triplicate measurement of samples from the actual seed suspension.

Analysis for concentrations of *Cryptosporidium* was performed using membrane filtration completed by immunofluorescence assay (IFA) and microscopy.[3,4,5,9] All analyses were made quantitative by using seeded recovery efficiency samples (positive controls) for each batch of samples assayed during each testing period. Analytical results were expressed exclusively in terms of true concentration (organisms per litre). All *Cryptosporidium* oocysts used were isolated from fresh fecal samples from dairy calves.

- Performance tests to characterize principal conditions were repeated three times.

> For each DE grade, lower removal corresponded to runs with the lowest head loss rates.

Methods

Testing arrangements. The project was conducted in the Department of Water Engineering laboratories at the University of New South Wales, Sydney, Australia. Water was obtained from a local surface source identical to that used for the public water supply. Typical water quality characteristics included low turbidity (1.0–1.4 ntu) and near-neutral pH (6.8–7.1). Background concentrations of *Cryptosporidium* oocysts were determined in independent work to be <0.5/L. Water used for each batch of tests was characterized for turbidity.* The concentration of particles >1 µm in the raw water was typically between 4 and 7 X 10^3/mL. Testing began in June 1996 and ended in February 1997.

Organisms. *Cryptosporidium* oocysts were purified by isolation from fresh feces of calves. Samples were collected approximately monthly from a 2,700-head dairy herd near Camden, N.S.W., on the western fringe of the Sydney metropolitan area. Typically, about 50 percent of samples from calves up to a month old were positive. Oocysts were isolated and purified by washing, concentration on Sheather's sucrose, and cleanup on Percoll.†[8,10] Cleaned and counted oocysts were stored in filter-purified water‡ for up to a month before use.

Organisms were prepared for seeding by counting using haemocytometer and drop-counting procedures.[8] Seed concentrations ranged up to >10^7/L to allow measurement of concentration reductions anticipated to be as much as 6 logs.

A rigorous scheme of counting, checking, and measuring recovery efficiency was used to establish concentrations needed to calculate treatment performance. The scheme (Figure 1) consisted of preparing from stock an 11-mL working suspension of *Cryptosporidium* oocysts in a 15-mL test tube. This was the common

*Hach 1700a turbidimeter, Hach Co., Loveland, Colo.
†Percoll, Sigma, St. Louis, Mo.
‡MilliRO, Millipore, Bedford, Mass.

TABLE 2 Cryptosporidium removals for DE test filter runs conducted at 1 gpm/sq ft (2.4 m/h)

Run Number	DE Grade	CC* Average ± Standard Deviation (n = 3)	Seed Concentration *oocysts/L*	AR/CC = Recovery Fraction	Oocysts in Sample	Log Reduction
5	A1	255 ± 50.7	1.02×10^7	175/255 = 0.686	2/0.68 = 2.9	6.53
	B1	255 ± 50.7	1.02×10^7	189/255 = 0.741	3/0.74 = 4.1	6.41
14	A1	491 ± 44.5	2.46×10^7	324/491 = 0.659	15/0.66 = 22.7	6.03
	B1	491 ± 44.5	2.46×10^7	385/491 = 0.784	14/0.78 = 17.9	6.13
15	A1	491 ± 44.5	2.46×10^7	324/491 = 0.659	11/0.66 = 16.7	6.16
	B1	491 ± 44.5	2.46×10^7	385/491 = 0.784	8/0.78 = 10.2	6.38
1	A2	486 ± 18.4	9.72×10^6	249/486 = 0.512	6/0.51 = 11.7	5.92
	B2	486 ± 18.4	9.72×10^6	430/486 = 0.885	11/0.88 = 12.4	5.89
2	A2	1,046 ± 176	2.09×10^7	953/1,046 = 0.911	21/0.91 = 23	5.96
	B2	1,046 ± 176	2.09×10^7	904/1,046 = 0.864	14/0.86 = 16.2	6.11
8	A2	906 ± 57.8	1.81×10^7	798/906 = 0.881	12/0.88 = 13.6	6.12
	B2	906 ± 57.8	1.81×10^7	670/906 = 0.739	22/0.74 = 29.7	5.79
3	A3	725 ± 75.8	1.45×10^7	599/725 = 0.826	2,740/0.83 = 3,317	3.64
	B3	725 ± 75.8	1.45×10^7	578/725 = 0.797	2,882/0.79 = 3,616	3.60
4	A3	592 ± 27.8	1.18×10^7	545/592 = 0.921	593/0.92 = 644	4.26
	B3	592 ± 27.8	1.18×10^7	529/592 = 0.893	329/0.89 = 368	4.51
9	A3	906 ± 57.8	1.81×10^7	540/906 = 0.596	2,636/0.60 = 4,393	3.62
	B3	906 ± 57.8	1.81×10^7	806/906 = 0.889	2,992/0.89 = 3,362	3.73

*AR—actual recovery; CC—concentration check

TABLE 3 Cryptosporidium removals for DE test filter runs conducted at 2 gpm/sq ft (4.9 m/h)

Run Number	DE Grade	CC* Average ± Standard Deviation (n = 3)	Seed Concentration *oocysts/L*	AR/CC = Recovery Fraction	Oocysts in Sample	Log Reduction
16	A1	433 ± 12.2	2.17×10^7	393/433 = 0.908	6/0.91 = 9.9	6.33
	B1	433 ± 12.2	2.17×10^7	382/433 = 0.882	4/0.88 = 4.5	6.68
6	A2	839 ± 26.2	1.68×10^7	648/839 = 0.772	14/0.77 = 18.1	5.97
	B2	839 ± 26.2	1.68×10^7	628/839 = 0.748	15/0.75 = 20.0	5.92
10	A2	1,191 ± 106.8	2.38×10^7	1,055/1,191 = 0.886	8/0.89 = 9.0	6.42
	B2	1,191 ± 106.8	2.38×10^7	953/1,191 = 0.800	2/0.80 = 2.5	6.48
13	A2	763 ± 64.9	1.53×10^7	523/763 = 0.685	3/0.69 = 4.4	6.54
	B2	763 ± 64.9	1.53×10^7	575/763 = 0.754	6/0.75 = 8	6.28
7	A3	839 ± 26.2	1.68×10^7	733/839 = 0.874	49/0.87 = 56.1	5.48
	B3	839 ± 26.2	1.68×10^7	669/839 = 0.797	18/0.80 = 22.6	5.87
11	A3	475 ± 26.5	9.50×10^6	444/475 = 0.934	32/0.93 = 34.2	5.44
	B3	475 ± 26.5	9.50×10^6	476/475 = 1.00	93/1.0 = 93	5.01
12	A3	475 ± 26.5	9.50×10^6	444/475 = 0.934	7/0.93 = 7.5	6.01
	B3	475 ± 26.5	9.50×10^6	476/475 = 1.00	51/1.0 = 51	5.27

*AR—actual recovery; CC—concentration check

source of seed, both for two test filter runs and for a set of five controls used to accurately establish concentrations and recovery efficiencies. The concentration of the working suspension was prepared from stock oocysts in the range 1–2 X 10^6/mL (based on haemocytometer counts) to provide for measurable effluent concentrations expected based on preliminary testing.

From the 11-mL suspension, two 5-mL aliquots were reserved as seed for the two test filter runs. A 500-µL aliquot was diluted to 100 mL to be used for concentration checks (CCs) run in triplicate (CC1, CC2, and CC3) and for measurement of recovery efficiency (actual recovery [AR]; AR-DE1 and AR-DE2) in the effluent from each filter. This was measured by adding a 100-µL aliquot of the 200:1 diluted seed (containing ~1,000 oocysts) to 250 mL of filtrate. The filtrate was produced during midrun before seed was added to the filter influent from the two DE test filters paired in each run (Figure 1).

Cryptosporidium concentration measurement. The concentration of *Cryptosporidium* oocysts was determined by filtration of all samples onto 2-µm-pore-size etched-pore polycarbonate filters* and staining with IFA antibodies† for *Cryptosporidium*. Concentration checks were filtered directly onto 0.5-in.-(13-mm-) diameter filters in in-line filter holders, where they were stained, incubated, and rinsed. They were then mounted on glass slides with elvanol under coverslips.[5] Confirmation of objects as *Cryptosporidium* was not a concern, because the concentration of *Cryptosporidium* added was >6 logs greater than background concentrations.

The 2-L samples collected from the Walton test filters during seeding (DE1 and DE2) and the recovery efficiency controls (AR-DE1 and AR-DE2) were analyzed by first filtering onto 1.9-in.- (48-mm-) diameter fil-

*Poretics, Livermore, Calif.
†Crypt-a-Glo, Waterborne Inc., New Orleans, La.

ters, recovering particles by squeegeeing and rinsing three times[8] and then filtering onto the final 0.5-in.- (13-mm-) diameter filters for IFA assay. Concentrations were calculated by counting organisms found on the sample filter and adjusting by the AR determined from the average of the three concentration checks and the recovery measurements for each DE grade.

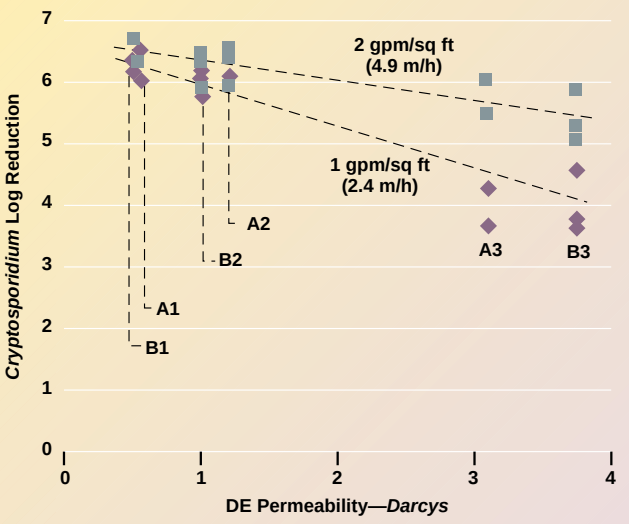
DE. DE was obtained from commercial stocks of manufacturer A* and B.† Three grades of DE were obtained from each source in pairs matched as closely as possible from available products. A1,‡ A2,§ and A3** were obtained from manufacturer A. B1,†† B2,‡‡ and B3§§ were obtained from manufacturer B. A2 and B2 are comparable grades, used most commonly for water filtration. The finer grades, A1 and B1, were suited to filtration of supplies with lower concentrations of finer particles than most surface water. A3 and B3 were coarser and suited to higher concentrations of larger-particle suspensions. Table 1 summarizes the general characteristics of the DE grades.

The DE grades from the two sources were tested in pairs; each pair constituted a run. Three runs were made for each pair of grades. The DE for each run was taken from the stock bag and weighed as appropriate to be used for precoat and bodyfeed applications.

Laboratory apparatus and operation. Two Walton filters[11] (Figure 2) were used for testing. The Walton filter is commonly used in the DE industry to determine the basic applicability of products to specific applications, because it is judged to accurately predict large-scale applications.[11] The filter is a 2-in.- (50-mm-) diameter lucite cylinder fitted with a stainless-steel support screen (septum) and with appropriate inlet and outlet fittings with valves for flow control. Flow is provided by a single-shaft, dual-head, positive-displacement pump.** Flow is adjusted by regulating rotational speed and by checking flow rates according to volume delivered per unit of time.

Precoat and bodyfeed concentrations were set as a result of preliminary testing at 20 lb/100 sq ft (1 kg/m^2) and at 40 mg/L, respectively. Precoat and bodyfeed suspensions were prepared in batches for each run and were applied from solution in containers that were mechanically mixed. Runs were made at 1 and 2 gpm/sq ft (2.4 and 4.9 m/h) using the precoat and bodyfeed concentrations cited. Runs were typically maintained for 120–180 min and were monitored to determine head loss accumulation and reductions in turbidity. Monitoring was continuous over the period of operation for each run.

FIGURE 3 Log reductions in Cryptosporidium oocysts as a function of DE permeability



Calculations. Three types of calculations were included in this project: (1) calculations of log reduction, (2) calculations of *Cryptosporidium* oocyst concentration, and (3) tests of statistical significance. Calculations were made as follows.

Log reduction. Log reductions in *Cryptosporidium* concentration were calculated as the difference between the $\log_{10}$ of the influent concentration and the $\log_{10}$ of the filtrate concentration.

Cryptosporidium oocyst concentration. The concentration of oocysts was measured directly for influent samples. For filtrate samples, loss of oocysts was quantified by measuring the AR using a procedure identical to that used to analyze filtrate samples. The concentration of oocysts actually present in filtrate samples was calculated as follows:

Oocyst concentration, number/ L =
oocysts in sample ÷ (AR fraction X sample volume, L)

> The increase in flow rate resulted in greater removal, although the rate of head loss accumulation was increased for each pair of DE grades.

*Celite Corp., Lompoc, Calif.
†Eagle–Picher Minerals Inc., Reno, Nev.
‡Celite 512, Celite Corp., Lompoc, Calif.
§Celite Hyflo Super-Cel, Celite Corp., Lompoc, Calif.
**Celite 535, Celite Corp., Lompoc, Calif.
††Celatom FW-6, Eagle–Picher Minerals Inc., Reno, Nev.
‡‡Celatom FW-12, Eagle–Picher Minerals Inc., Reno, Nev.
§§Celatom FW-50, Eagle–Picher Minerals Inc., Reno, Nev.
**MasterFlex, Cole–Parmer, Chicago, Ill.

FIGURE 4 Log reduction of Cryptosporidium oocysts as affected by filtration rate and DE grade and permeability

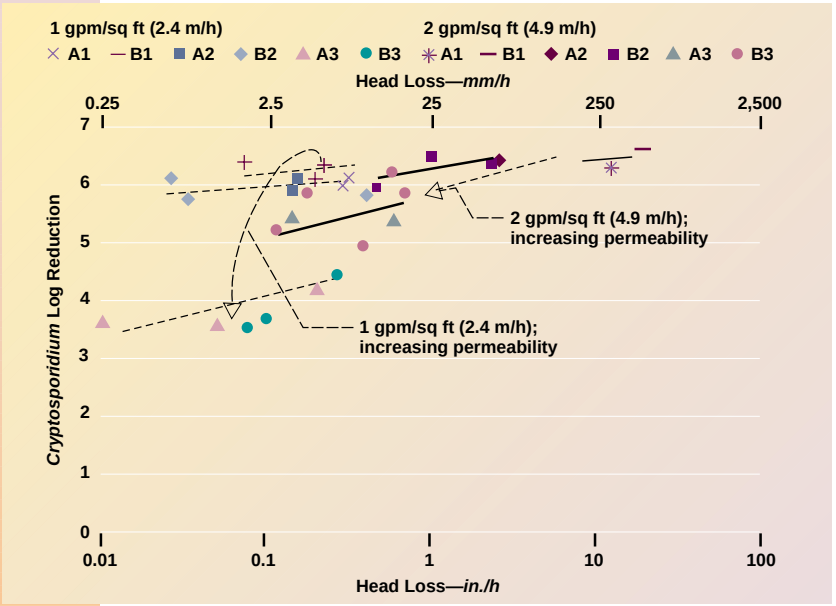


Illustration of the concentration calculations is provided in columns 5–7 of Tables 2 and 3.

Statistical tests. Standard statistical tests were used to determine whether differences in the performance of test filters with different materials and conditions were significant.

- The paired *t*-test was used to determine whether the mean of log reductions observed for one of the pair of grades tested at a single filtration rate was greater than the mean of log reductions observed from the other of the grade pair. The value of *t* was calculated by the following formula:

$$t = d \div (sd \div \sqrt{n}),\ df = n - 1,\ \text{for } n = 3 \qquad (1)$$

in which *t* = test statistic, *d* = difference between sample means, *sd* = standard deviation, *n* = number of observations, and *df* = degrees of freedom ($n - 1$).

- The *t*-test was used to make two determinations. First, it determined whether—for six runs for both materials in a selected grade (fine, medium, or coarse) at a single filtration rate—the mean of log reductions was greater than that for the six runs for both materials in a different selected grade. Second, it determined whether for six runs for both materials in a selected grade, the mean of log reductions for one filtration rate was greater than that for six runs for the same materials at the other rate. For this procedure, *t* was calculated by the following formula:

$$t = (x_1 - x_2) \div [(sd_1^2/n_1) + (sd_2^2/n_2)]^{1/2},\ df = n_1 + n_2 - 2,\ \text{for } n_1 = n_2 = 6 \qquad (2)$$

Critical values of *t* for the appropriate degrees of freedom were taken from standard tabulations of the *t*-statistic.

Results

Large reductions in concentrations of *Cryptosporidium* oocysts were observed from operation of test filters at 1 gpm/sq ft (2.4 m/h), ranging as follows: 6.03–6.53 logs for the finest grades of DE (A1 and B1), 5.79–6.12 logs for the middle grades (A2 and B2), and 3.60–4.51 logs for the coarser grades (A3 and B3; Table 2). Reductions observed from operation at 2 gpm/sq ft (4.9 m/h) were higher: 6.33–6.68 logs for the finest grades, 5.92–6.54 logs for the middle grades, and 5.01–6.01 logs for the coarser grades (Table 3). The differences in log reductions for the different grades were approximately in inverse proportion to the permeability of the grade (Figure 3).

Replication between runs as characterized by the standard deviations and coefficients of variation were typically ~5 percent (Table 4). For the 18 runs at 1 gpm/sq ft (2.4 m/h), the average coefficient of variation was 5.5 percent (range = 1.83–12.4 percent); for the 14 runs at 2 gpm/sq ft (4.9 m/h), the average coefficient of variation was 5.7 percent (range = 4.49–8.18 percent). (Carefully completed haemocytometer counts of seed preparations differed from actual numbers calculated from the three CC samples by a factor of as much as two to three, both higher and lower than actual.)

The differences between the observed log reductions for each pair of DE grades and for both flow rates were tested for statistical significance using the paired *t*-test. According to this test, none of the differences in average log removal between the pairs of a single grade (i.e., between A1 and B1, A2 and B2, and A3 and B3) was significant at $t \leq 0.10$.

Test results for the three grades were pooled and tested using a single tailed *t*-test. For $t \leq 0.01$, the difference in the average of observed log reductions at 1 gpm/sq ft (2.4 m/h) for the fine grades, $x = 6.27$ log and $s = 0.194$, was significantly greater than that for the medium grades, $x = 5.97$ log and $s = 0.129$ (Table 4). Similarly, using the same test and for $t \leq 0.01$, the difference in the average of observed log reductions at 2 gpm/sq ft (4.9 m/h) for the medium grades, $x = 6.28$ log and $s = 0.265$, was significantly greater than that for the coarse grades, $x = 5.51$ log and $s = 0.372$ (Table 4). The differences between other pairs of grades, being greater, were also significant at $t \leq 0.01$.

Log reductions observed for runs conducted at a filtration rate of 2 gpm/sq ft (4.9 m/h) were higher than for runs conducted at a filtration rate of 1 gpm/sq ft (2.4 m/h; Table 4). Results for the pooled

grades were tested to determine whether the change in flow rate significantly changed log reduction. Use of the single tailed *t*-test showed that the difference between the average observed log reduction for A2 and B2 at 2 gpm/sq ft (4.9 m/h), $x = 6.28$ log and $s = 0.265$, was significantly greater than for the same grades at 1 gpm/sq ft (2.4 m/h), $x = 5.97$ log and $s = 0.129$, for $t \leq 0.01$. By the same test, the average log reduction for the coarse grades, A3 and B3, at 2 gpm/sq ft (4.9 m/h), $x = 6.27$ log and $s = 0.194$, was significantly greater than for the same grades at 1 gpm/sq ft (2.4 m/h), $x = 5.51$ log and $s = 0.372$, for $t \leq 0.01$.

TABLE 4 Average log reductions of Cryptosporidium oocysts for six DE products

DE Grade	Log Reduction at 1 gpm/sq ft (2.4 m/h)		Log Reduction at 2 gpm/sq ft (4.9 m/h)	
	Average	Standard Deviation ($n = 3$)	Average	Standard Deviation ($n = 3$)
A1	6.24	0.26	6.33	NA*
B1	6.31	0.15	6.68	NA
A2	6.00	0.11	6.31	0.31
B2	5.93	0.16	6.23	0.28
A3	3.84	0.36	5.64	0.32
B3	3.94	0.49	5.38	0.44

*NA—not applicable

The decrease in observed log reductions with increasing permeability was mirrored by decreases in the rate of head loss accumulation (Figure 4). The increase in flow rate resulted in greater removal, although the rate of head loss accumulation was increased for each pair of DE grades. Toward the left side of Figure 4, the data from 1-gpm/sq ft (2.4-m/h) runs show head losses in the range 0.01–0.3 in./h (0.25–7.5 mm/h). The coarsest DE (lower left, Figure 4) removed the least, and the finest DE (upper left, Figure 4) removed the most. For each DE grade, lower removal corresponded to runs with the lowest head loss rates (e.g., dashed line through circles and triangles at lower left of the figure). An analogous pattern can be seen for the runs conducted at 2 gpm/sq ft (4.9 m/h) at the upper center and right of Figure 4. As with the runs at lower flow rates, higher removals corresponded to runs having higher head loss rates.

Diatomaceous earth filtration should be seriously considered among practical alternatives for treating Cryptosporidium in surface water.

Discussion

The finding of principal interest is the clear capability of DE filtration to provide far greater reduction in *Cryptosporidium* oocyst concentrations than is provided by conventional or direct granular media filtration. The apparent adaptability of DE filtration to provide 6 logs of removal under conditions practical in full-scale water treatment—operation at 1–2 gpm/sq ft (2.4–4.9 m/h) using DE of moderate permeability (A2 and B2)—offers a degree of control not demonstrated by any other treatment process in use today. Previous work has shown that DE filtration can control protozoan cysts, but the capabilities have not been clearly defined. Several studies suggest that DE filtration should provide ~3 logs reduction in the concentration of *Giardia* cysts.[12,13] Other work suggests it would provide >3 logs reduction in the concentration of *Cryptosporidium* oocysts.[14]

Data in this article demonstrate logical relationships between log removal and the grade or permeability of DE used and between log removal and filtration rate consistent with descriptions of DE filtration performance in the literature. The efficiency of DE filtration for removing particles of a given size depends on the effective size and permeability of the DE grade used. The greater the permeability, the lower the removal for particles of a given size (Figure 3).

The principal effect of increasing the filtration rate for a given DE grade and water quality is to increase the pressure against the cake building up on the support septum. The rate of head loss accumulation increases with increasing filtration rate and with decreasing permeability (Figure 4). The DE bodyfeed provides a relatively rigid structure to maintain cake permeability. However, with increasing pressure, the increasing rate of head loss accumulation suggests that some cake compression occurs, apparently reducing the effective permeability. Higher log reductions at higher filtration rates and at higher head loss rates (Figure 4) are consistent with effective reduction in permeability at those operating conditions.

Data introduced in this study have benefited by greater analytical sensitivity attributable to advances in techniques and application of control principles. It has been possible to directly measure reductions in *Cryptosporidium* oocyst concentrations >6 logs. Statis-

tical inferences depend entirely on the quality control and sampling design employed (Figure 1). The quality of the data may also illustrate the general performance capabilities of this application of membrane filtration to analysis of oocyst concentrations. Overall recovery efficiencies for AR samples at 1 gpm/sq ft (2.4 m/h) averaged 78 percent (s = 12 percent and n = 18; Table 2). For AR samples at 2 gpm/sq ft (4.9 m/h), the average is 84 percent (s = 10 percent and n = 12; Table 3).

Such levels of recovery cannot, however, be expected from processing surface water samples to measure *Cryptosporidium* concentrations. For such applications, a gradient concentration step would be required that would reduce overall recovery efficiency to about 20 percent.[5]

Results of Walton filter tests showing ~6 logs of *Cryptosporidium* oocyst reduction provide a basis for calculating the number of oocysts needed to seed a larger-scale pilot-test apparatus. This—in conjunction with processing restrictions dictating the use of filtered water samples up to 2-L volumes—will permit researchers to plan an appropriate seeding and sampling sequence for such larger-scale tests.

Analytical methods described in this study, particularly the scheme of controls used to establish concentrations, were time-consuming but essential to describing performance. This approach yielded information that permits thorough, objective evaluation of the data. For example, haemocytometer counts have, in the authors' hands, proved unreliable as a way to describe concentration accurately enough to avoid underestimating concentration. Such underestimation could easily mean that no oocysts would be found in filtrate samples, limiting the results of that run to only qualitative interpretation.

Conclusion

The finding of >6 logs of *Cryptosporidium* removal for DE grades commonly and economically used by smaller water systems is highly attractive and should be the subject of further investigation. DE filtration should be seriously considered among practical alternatives for treatment of surface water.

The potential that *Cryptosporidium* can be this effectively controlled suggests several possibilities for application in municipal water treatment. It might be possible to relax the operation of existing conventional granular media filters and to use DE filters for polishing. The range of community sizes for which DE filtration has been considered economical may be expanded considerably when measured against alternative control methods.

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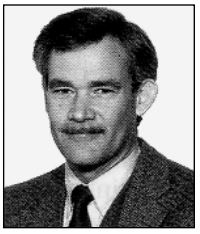

About the authors: *Jerry E. Ongerth is currently an adjunct professor in the Department of Water Engineering, University of New South Wales, Department of Water Engineering, Sydney, NSW 2052, Australia. He is also an adjunct professor in civil engineering in the Department of Environmental Health, University of Washington in Seattle. Ongerth has spent 20 years as a teacher, researcher, and engineer in the field of water supply and treatment. He has published extensively on* Cryptosporidium *and* Giardia. *He is a member of AWWA, WEF, and AAEE and has received AWWA's best paper award for the Water Quality Division. P.E. Hutton is a research fellow in the Department of Water Engineering at the University of New South Wales.*