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Pilot-scale testing of diatomaceous earth filtration for removal of Cryptosporidium oocysts

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executive summary

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Testing of DIATOMACEOUS Earth Filtration

FOR REMOVAL OF *CRYPTOSPORIDIUM* OOCYSTS

Because previous studies of diatomaceous earth (DE) filtration for *Cryptosporidium* oocyst removal have been conducted on a relatively small scale, this study was designed to determine the performance capability of DE at the pilot-scale level and at a flow rate greater than that permitted by many state regulatory agencies. This study used DE of moderate permeability that is commonly used by smaller water systems to provide economical water treatment. It found that *Cryptosporidium* oocyst removals at a flow rate of 1 gpm/sq ft (2.5 m/h) averaged 6.25 logs and removals at 2 gpm/sq ft (5 m/h) averaged 6.31 logs. In addition, average turbidity levels and particle concentrations were lower at 2 gpm/sq ft (5 m/h). These findings of equal or better performance at 2 gpm/sq ft (5 m/h) are significant because many regulatory agencies—and consequently municipal water suppliers—have historically restricted operation of DE filters to 1 gpm/sq ft (2.5 m/h). The findings are also important because they clearly show that DE filtration is capable of providing far greater reduction in *Cryptosporidium* oocyst concentrations than is provided by conventional or direct granular media filtration.

The data summarized in this article support consideration of DE as a more broadly applicable alternative for *Cryptosporidium* control; they also support including DE filtration as a serious alternative for a much broader range of applications—including larger plant sizes, higher filtration rates, and backwash treatment applications.—GSM

Jerry E. Ongerth and Primrose E. Hutton

A pilot-scale diatomaceous earth (DE) filter was operated while seeding with *Cryptosporidium* to measure oocyst removal performance. Turbidity and particle removals were also measured. Operating conditions for testing runs included the following: DE permeability = 1.0–1.2 darcies, precoat = 1 kg/m^3 (20 lb/100 sq ft), and bodyfeed = 5 mg/L. *Cryptosporidium* seeding levels were 1–8 × 10^6/L. Three runs were made at both 1 and 2 gpm/sq ft (2.5 and 5 m/h). For each run, three independent sets of *Cryptosporidium* removal measurements were made. *Cryptosporidium* removals for runs at 1 gpm/sq ft (2.5 m/h) averaged 6.25 logs. Removals for runs at 2 gpm/sq ft (5 m/h) averaged 6.31 logs. Average performance for both turbidity and particle removal were also better at 2 gpm/sq ft (5 m/h). Results show that 6-log removals of *Cryptosporidium* can be expected from DE filtration. DE filter operation at 2 gpm/sq ft (5 m/h) should be considered advantageous. Operation at even higher application rates should be considered when alternatives for *Cryptosporidium* control are compared.

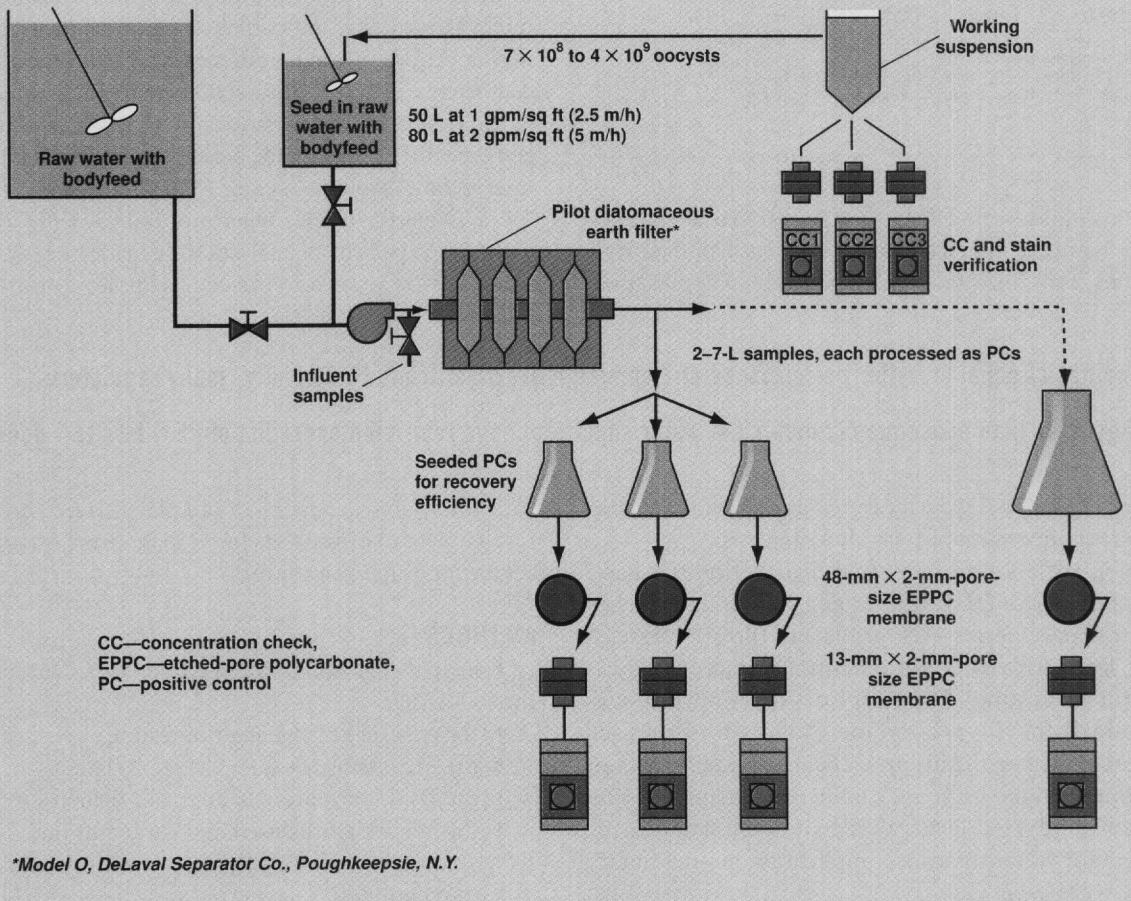
Testing of DIATOMACEOUS Earth Filtration

FOR REMOVAL OF *CRYPTOSPORIDIUM* OOCYSTS

The control of *Cryptosporidium* oocysts by water treatment processes is of major interest to public water suppliers and public health agencies. The concentrations of *Cryptosporidium* in water continue to become better defined, reinforcing the view that the organism must be considered to be present in all surface waters (Hsu et al, 1999; Karanis et al, 1998; States et al, 1997; Hutton & Ongerth, 1993). Waterborne outbreaks of cryptosporidiosis continue to be reported; although occurrences of the disease are rare when compared with the total days of service provided by all surface water utilities between outbreaks, the number of occurrences underscore the need for consistent, high-quality treatment to minimize the risk of outbreaks. The

BY JERRY E. ONGERTH AND PRIMROSE E. HUTTON

FIGURE 1 *Cryptosporidium* seeding and concentration assay used in log removal runs



resistance of *Cryptosporidium* to disinfectants continues to emphasize the importance of physical removal, which is typically accomplished by filtration processes (Robertson et al, 1994).

Previous work (Ongerth & Hutton, 1997; Ongerth & Pecoraro, 1995) has suggested that diatomaceous earth (DE) filtration has potential for providing outstanding *Cryptosporidium* removal. In recent work, 6-log removals of *Cryptosporidium* oocysts were reported (Ongerth & Hutton, 1997). This removal is on the order of a thousandfold (3 logs) greater than that typically offered by conventional filtration (Ongerth & Hutton, 1997; Nieminski & Ongerth, 1995; Ongerth & Pecoraro, 1995; Ongerth, 1990; Schuler & Ghosh, 1990). In the previous DE filtration work (Ongerth & Hutton, 1997), industry-standard 15-cm^2 Walton test filters (Walton, 1978) were used to determine the control potential of DE filtration using three different DE grades and filtration rates of 1 and 2 gpm/sq ft (2.5 and 5 m/h).

OBJECTIVES

This project was conducted to verify the previous findings of 6-log oocyst removal using a pilot-scale, four-leaf DE filter. The specific objectives of the project were

- to determine the degree of *Cryptosporidium* oocyst control provided by DE filtration operated under typical water treatment conditions,
- to determine the consistency of the treatment performance,
- to determine the relationship between oocyst reduction and filtration rate, and
- to characterize DE filter performance in terms of *Cryptosporidium* removal and in terms of both turbidity and particle counts.

APPROACH

The approach used in this project was based on that cited in the previously reported work (Ongerth & Hutton, 1997). Surface water (~1 ntu) was seeded with *Cryptosporidium*

TABLE 1 Summary of DE* characteristics used for measurement of *Cryptosporidium* removal

DE Grade	Median Size *μm*	Permeability *darcy*
DE-A†	22.3	1.2
DE-B‡	24	1.0

*DE—diatomaceous earth
†Celite Hyflo Super-Cel®, Celite Corp., Lompoc, Calif.
‡Celatom® FW-12, Eagle–Picher Minerals Inc., Reno, Nev.

oocysts. A pilot-scale DE filter was operated at filtration rates of 1 and 2 gpm/sq ft (2.5 and 5 m/h), each for three replicate runs (runs 1–3 and 4–6, respectively). *Cryptosporidium* oocysts were measured using membrane filter and immunofluorescence assay (IFA) analysis.

Bench-scale studies were used to define the basic characteristics of DE filtration as a function of the 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 filtration rate was determined for a typical grade of DE currently used for potable water filtration. General characteristics of the DE used in the study are summarized in Table 1. Precoat and bodyfeed levels that had been found to be effective for water treatment application in preliminary testing were used.

Cryptosporidium oocysts were seeded continuously during performance testing periods. Unpreserved fresh organisms produced at approximately monthly intervals as an integral part of the project were used for all seeding studies. Counting to establish seed concentrations was confirmed by triplicate measurement of samples taken from the actual seed suspension. Filter performance was evaluated in terms of oocyst removal, turbidity, and particle count measurements made during periods of continuous seeding. Performance tests to characterize principal conditions were repeated three times.

Analysis for concentrations of *Cryptosporidium* was performed using membrane filtration completed by IFA and microscopy (Nieminski et al, 1995; Hansen & Ongerth, 1991; Ongerth, 1989; Ongerth & Stibbs, 1987). During each testing period, all analyses were made quantitative by using seeded recovery efficiency samples (positive controls [PCs]) for each batch of samples assayed. Analytical results were expressed exclusively in terms of true concentration (organisms/litre).

The findings of equal or better performance at 2 gpm/sq ft are significant. Historically, many regulatory agencies (and consequently municipal water suppliers) have restricted operation of DE filters to 1 gpm/sq ft.

METHODS

Principal elements of the methodology used included the following:

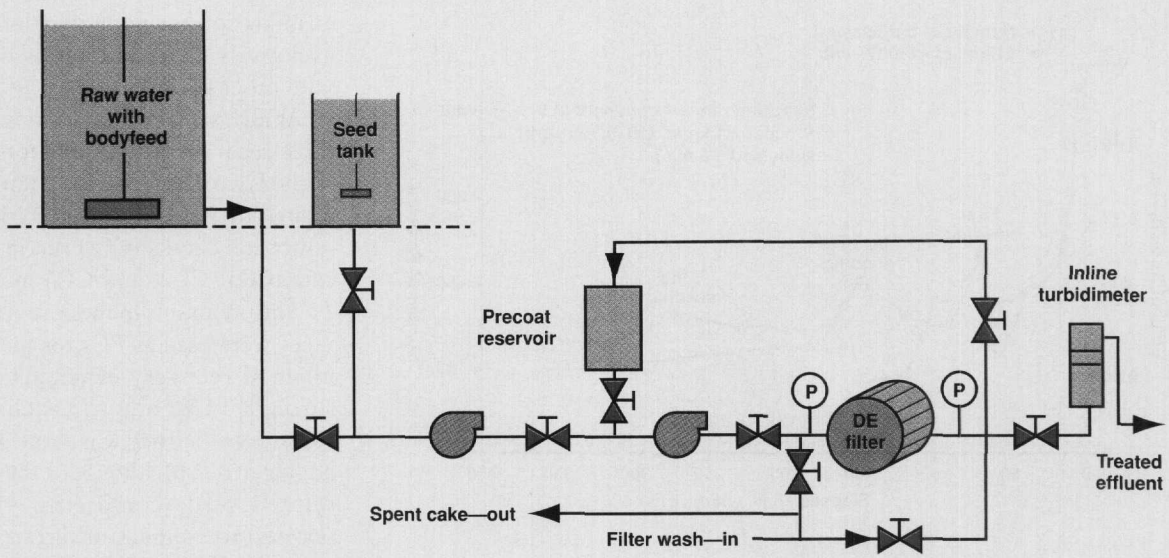
- the general arrangement of testing;
- the organisms used;
- the DE filter materials used and their condition;
- the lab apparatus used and its operation;
- seeding, sampling, and sample analysis; and
- calculations.

TABLE 2 Diatomaceous earth test filter for *Cryptosporidium* removal—runs at 1 gpm/sq ft (2.5 m/h)

Run	Date	Δp* *psi (kPa)*	Run Time at Seeding *min*	Turbidity *ntu*		Particles/mL		*Cryptosporidium* Concentration—*oocysts/L*		Log Removal
				In	Out	In	Out	In	Out	
1a	4/22/98	2.0 (14)	70	0.88	0.10	4,581	225	8.15×10^6	2.84	6.45
1b	4/22/98	3.0 (21)	150		0.09		153	8.15×10^6	4.70	6.24
1c	4/22/98	4.6 (32)	270	0.88	0.07		110	8.15×10^6	5.64	6.16
Average				0.88	0.07	4,581	105		4.39	6.28
2a	4/29/98	N/A	110	0.75	0.11	4,363	343	6.14×10^6	4.86	6.10
2b	4/29/98	N/A	190		0.08	4,337	405	6.14×10^6	4.34	6.15
2c	4/29/98	N/A	260	0.74	0.06		262	6.14×10^6	4.74	6.11
Average				0.75	0.09	4,350	250		4.65	6.12
3a	5/4/98	N/A	140	1.1	0.14	4,162	293	1.4×10^6	1.08	6.11
3b	5/4/98	N/A	190		0.13		373	1.4×10^6	0.54	6.41
3c	5/4/98	N/A	255	1.04	0.10		352	1.4×10^6	0.36	6.53
Average				1.07	0.10	4,162	185		0.66	6.35

*In Δp, *p* means pressure.

FIGURE 2 DE filter used for *Cryptosporidium* log reduction measurement



DE—diatomaceous earth, P—pressure gages

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 public water supply. Typical water quality characteristics included low turbidity (0.8–1.2 ntu) and near-neutral pH (6.8–7.1); particle and phytoplankton characteristics were typical of water supply reservoirs in areas with moderate Mediterranean climates, with total particles at (1.5–12.5 µm) ~4,000–6,000/mL. Water used for each batch of tests was characterized for turbidity and particle counts. Turbidity of raw water was measured using a bench turbidimeter.* During filter runs, the turbidity of filtrate was monitored continuously.† Particle concentrations in size ranges that correspond to the size of *Cryptosporidium* (3–5 µm) and to *Giardia* (7–12 µm) were measured for raw and filtered water. Particle concentrations within the size range of 1.5–12.5 µm were periodically measured in samples of filtrate.‡ Testing began in June 1997 and was completed in June 1998.

Organisms. As part of the project, *Cryptosporidium* oocysts used in this study were produced from fresh feces of Holstein–Friesian dairy calves (Ongerth & Hutton, 1997). Oocysts were isolated and purified by washing, concentrated on Sheather's sucrose, and cleaned up on Percoll§ (Ongerth & Pecoraro, 1996; Ongerth & Stibbs, 1989). Prior to use, cleaned and counted oocysts were stored in filter-purified water,** unpreserved, for up to a month.

Organisms were prepared for seeding using hemocytometer counts for estimation of numbers needed; however, membrane filter/IFA counting procedures were used for accurate definition of organism numbers. Seed levels required in this project were within a range that exceeded 10^7/L. A single run at 5 L/min (0.02 gps) required as much as 10^9 total organisms to permit measuring concentration reductions anticipated to be on the order of 6 logs.

A rigorous scheme of counting, checking, and recovery efficiency measurement was used to establish the concentrations needed to directly measure treatment performance. The scheme (Figure 1) consisted of preparing a working suspension of *Cryptosporidium* oocysts from stock for each filter run. This provided the seed for all the replicated measurements required to complete a single filter run. This procedure also included the accompanying controls required to establish the concentrations and recovery efficiencies needed for calculation of log reduc-

Although this study examined filtration rates of 1 and 2 gpm/sq ft, no practical reason can be foreseen that indicates a highly effective removal of *Cryptosporidium* by DE filters would not be found at even higher filtration rates.

*Hach 2100a turbidimeter, Hach Co., Loveland, Colo.
†Hach 1720c turbidimeter, Hach Co., Loveland, Colo.
‡Hiac Royco ARC-3, Hiac Royco, Grants Pass, Ore.
§Percoll, Sigma, St. Louis, Mo.
**Milli-RO, Millipore, Bedford, Mass.

FIGURE 3 Turbidity and particle counts over filtration time for seeded run 1

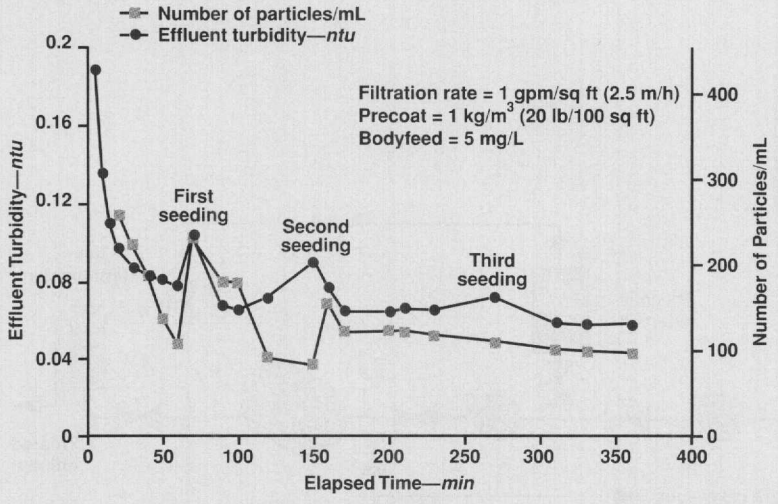
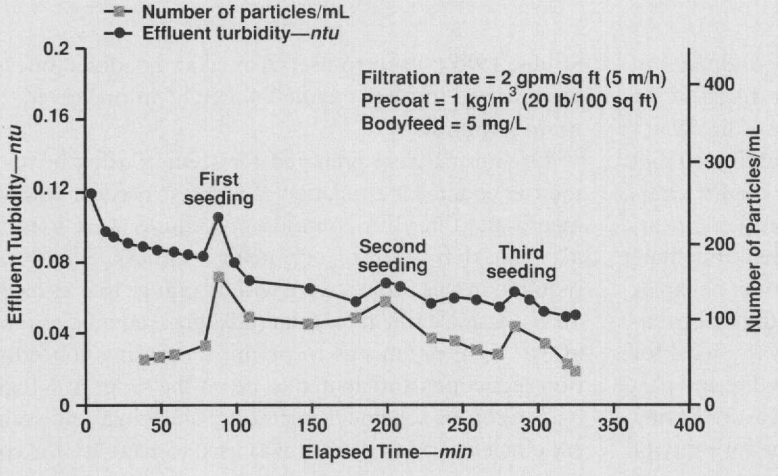


FIGURE 4 Turbidity and particle counts over filtration time for seeded run 4



tions. The concentration of the working suspension was initially estimated based on hemocytometer counts; it was then verified by replicated concentration checks performed by applying precisely measured volumes directly to 13-mm filters, which were then analyzed by IFA and microscopy.

Once counted, the working suspension was added to an appropriate volume (50 or 80 L, depending on the filtration rate for the run) of the feedwater containing bodyfeed that had been transferred to the separate mixed seed tank (Figure 2). As will be shown, although the *Cryptosporidium* seed and DE bodyfeed were maintained together (mixed) during the course of each run, no indication of association of the *Cryptosporidium* with the DE or particles in the bodyfeed volume was observed. The concentration of oocysts measured in the seed/bodyfeed tank was constant over the length of each run. In addition, oocysts observed during microscopic examination for quantification were exclusively clean and not associated with other particles.

At each sampling time during a run, three separate 500-µL aliquots were withdrawn from the seed tank and diluted to 50 mL to be used for concentration checks (CCs) run in triplicate (CC1, CC2, and CC3 in Figure 1). The organisms in these 50-mL volumes were used as PCs for measurement of recovery efficiency (PC1 through PC6, one for each run). Recovery efficiency was measured by adding a 100-µL aliquot of the 100:1 diluted seed (containing ~1,000 oocysts) to volumes of filtrate ranging from 2 to 7 L that had been taken during periods of nonseeding. These volumes were processed for concentration measurement by a procedure identical to that used for samples taken during seeding periods (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 membranes* and staining with IFA antibodies† for *Cryptosporidium*. The oocyst concentrations in the seed suspensions used were determined by CCs. These were analyzed by filtering precisely measured volumes of the seed suspensions directly onto 13-mm-diameter filters in inline filter holders,‡ where they were stained by IFA, incubated, and rinsed. They were then mounted on glass slides with elvanol (under coverslips) and enumerated by microscopic examination (Ongerth & Hutton, 1997). *Cryptosporidium* oocysts were seeded into the raw water at concentrations (measured at the filter inlet) that ranged from 1 to 8 × 10^6. The concentration of *Cryptosporidium* measured in the raw water averaged 1 oocyst/L. Accordingly, confirmation of objects was not a concern, because all organisms identified in the filtered water having standard *Cryptosporidium* oocyst IFA, size, and shape criteria would have been the *Cryptosporidium* added. No algal species with an appearance similar to that of *Cryptosporidium* were observed during sample analysis.

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

TABLE 3 Diatomaceous earth test filter for *Cryptosporidium* removal—runs at 2 gpm/sq ft (5 m/h)

Run	Date	Δp* psi (kPa)	Run Time at Seeding min	Turbidity ntu		Particles/mL		*Cryptosporidium* Concentration—oocysts/L		Log Removal
				In	Out	In	Out	In	Out	
4a	5/6/98	6.2 (42.7)	90		0.105	4,004	164	1.76×10^6	0.552	6.51
4b	5/6/98	9.2 (63.4)	200	0.68	0.069		107	1.76×10^6	0.469	6.58
4c	5/6/98	11.8 (81.3)	295	0.74	0.062		81	1.76×10^6	0.497	6.55
Average				0.7	0.06	4,004	80		0.510	6.55
5a	5/18/98	8.0 (55.2)	140	0.92	0.118	4,334	362	1.53×10^6	0.94	6.21
5b	5/18/98	10.1 (69.6)	222	0.95	0.08	4,157	238	1.53×10^6	0.863	6.25
5c	5/18/98	12.7 (87.6)	312	0.94	0.063	4,136	144	1.53×10^6	1.79	5.93
Average				0.94	0.055	4,209	145		1.19	6.13
6a	5/20/98	5.8 (39.9)	70	0.96	0.084	5,381	121	1.3×10^6	1.046	6.09
6b	5/20/98	9.8 (67.6)	167	1.05	0.068		34	1.3×10^6	0.545	6.38
6c	5/20/98	13.8 (95.1)	264	1.02	0.061	5,361	114	1.3×10^6	0.654	6.30
Average				1.01	0.065	5,371	115		0.75	6.26

*In Δp, *p* means pressure.

For each sampling time, three independent volumes of filter influent and filter effluent were collected for analysis. Influent samples of 50 mL were collected. Filtered water samples that were collected during runs ranged from 2 to 7 L in volume; larger volumes were used for runs with lower seed concentrations (Tables 2 and 3). Samples and PCs used to measure recovery efficiency were analyzed using membrane filters and IFA assay—essentially the same process as that described previously for the CCs (Ongerth & Hutton, 1997). As outlined earlier, oocyst concentrations in samples were calculated by enumerating organisms and adjusting by the actual recovery (AR) determined from the average of the three concentration checks and the recovery measurements for each run.

DE. DE was obtained from commercial stocks of manufacturer A* and manufacturer B.† The grade of DE used was as designated either by manufacturer A (DE-A‡) or manufacturer B (DE-B§). DE-A and DE-B are comparable and are the grades used most commonly for water filtration (Rees & Cain, 1990). General characteristics of the two DE grades are summarized in Table 1.

Filter apparatus and operation. A four-leaf filter** having a surface area of 620 cm^2 (0.667 sq ft) contained in an acrylic resin vessel was used for *Cryptosporidium*, particle, and turbidity removal testing and for head loss measurement. Flow was provided by a single-shaft, dual-head, positive-displacement pump.†† Flow was adjusted to desired levels by regulating pump speed and by checking the volume delivered per unit of time. The pump was fed from 1 m^3 (264.2 gal) tanks elevated to provide a positive pressure of 1.5–2.5 m (4.9–8.2 ft) (Figure 2).

Precoat and bodyfeed levels were set as a result of preliminary testing at 1 kg/m^3 (20 lb/100 sq ft) and at 5 mg/L, respectively. Using these operating parameters, runs were made at 1 and 2 gpm/sq ft (2.5 and 5 m/h). *Cryptosporidium* oocysts were fed continuously from the seed tank during the sampling and analysis periods (Figure 2). Runs were maintained typically for 240–480 min and were monitored to determine reductions in turbidity and in the number of particles in the size range that corresponds to that of the protozoan cysts. Head loss accumulation was monitored continuously over the period of operation for each run.

Calculations. Three types of calculations were made as an essential part of this project: (1) calculations of log reduction, (2) calculations of *Cryptosporidium* oocyst concentration, and (3) tests of statistical significance. Calculations were made exactly as described previously (Ongerth & Hutton, 1997).

Log reduction. Log reductions for this work 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 *Cryptosporidium* oocysts was measured directly for influent samples. For filtrate samples, procedural steps were used that resulted in loss of oocysts. The loss was quantified by measurement of the AR as described previously. The concentration of oocysts actually present in filtrate samples (the *Cryptosporidium* Concentrations—Out column of Tables 2 and 3) was calculated as follows:

$$\text{Oocyst concentration, number/L} = \text{Oocysts in sample} \div (\text{AR fraction} \times \text{Sample volume, L}) \quad (1)$$

*Celite Corp., Lompoc, Calif.
†Eagle–Picher Minerals Inc., Reno, Nev.
‡Celite Hyflo Super-Cel®, Celite Corp., Lompoc, Calif.
§Celatom® FW-12, Eagle–Picher Minerals Inc., Reno, Nev.
**Model O, DeLaval Separator Co., Poughkeepsie, N.Y.
††MasterFlex, Cole–Parmer Instrument Co., Chicago, Ill.

FIGURE 5 Head loss over filtration time for seeded run 4

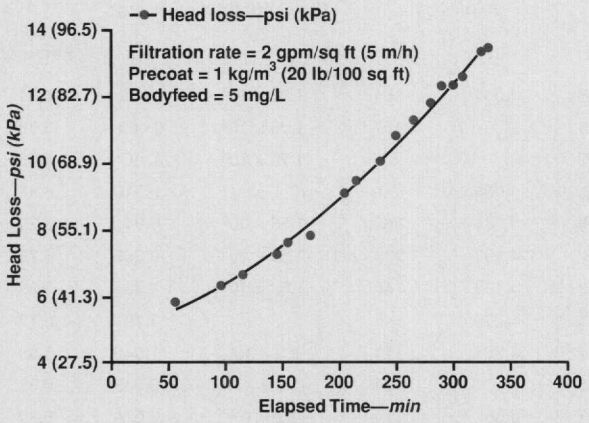


FIGURE 6 *Cryptosporidium* oocyst log reduction versus filtered water turbidity—runs at 1 and 2 gpm/sq ft (2.5 and 5 m/h) with normal filter operation and with pressure vibration

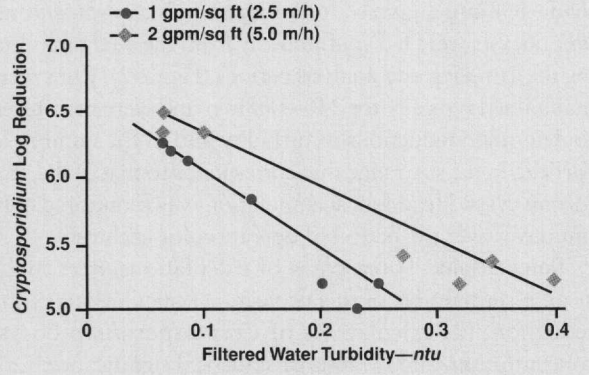
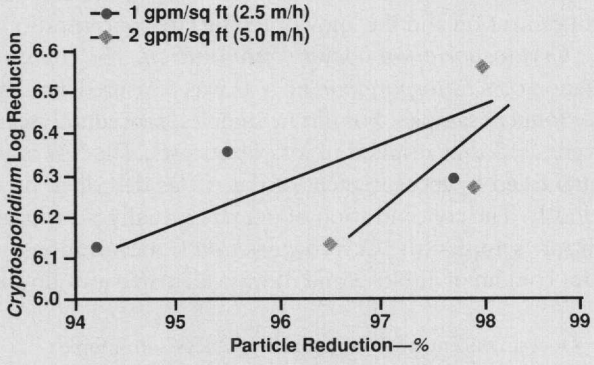


FIGURE 7 *Cryptosporidium* oocyst log reduction as a function of particle reduction for filter runs at 1 and 2 gpm/sq ft (2.5 and 5 m/h)



Statistical tests. A standard statistical test was used to determine whether differences in the performance of test filters under different operating conditions were significant. Specifically, the *t*-test was used to determine whether—for the three runs at one filtration rate—the mean of log reductions observed was greater than the mean of log reductions observed for the three runs conducted at the other filtration rate. For this procedure, t was calculated by the following formula:

$$t = (x_1 - x_2) \div [(sd_1^2/n_1) + (sd_2^2/n_2)]^{1/2},$$
$$df = n_1 + n_2 - 2, \text{ for } n_1 = n_2 = 9 \quad (2)$$

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

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

RESULTS

Pilot-scale testing was conducted in three sections. First, preliminary testing of the apparatus was conducted to determine general performance characteristics and to establish requirements for seeding and for sample analysis in order to ensure that interpretable *Cryptosporidium* data would be obtained. During this set of runs, the peristaltic pump supplied with the filter produced pressure fluctuations at the filter, which resulted in an inability to achieve turbidity levels less than 0.1 ntu. Data on *Cryptosporidium* removals under these conditions are described later under the heading DE filter runs at 1 and 2 gpm/sq ft (2.5 and 5 m/h) with pressure fluctuation. A hydraulic damper was added between the pump and the filter to limit pressure fluctuations to ± 1 psi (6.9 kPa). A second series of runs was conducted at a filtration rate of 1 gpm/sq ft (2.5 m/h). A final series of runs was conducted at 2 gpm/sq ft (5 m/h). Results for the three series of runs are described next.

DE filter runs at 1 gpm/sq ft (2.5 m/h). Reductions in *Cryptosporidium* oocyst concentrations observed for the three runs made at 1 gpm/sq ft (2.5 m/h) averaged from 6.12 to 6.35 logs (Table 2). The overall removal for the 1 gpm/sq ft (2.5 m/h) runs was 6.25 logs ± 0.17 (n = 9). Except for run 3, filtered water turbidity levels for the 1 gpm/sq ft (2.5 m/h) runs were consistently lower than 0.10 ntu, after the initial precoat stabilization period (Figure 3). Filtered water particle counts (total, 1.5–12.5 µm) averaged from 105 to 250/mL, compared with influent concentrations of 4,100 to 4,500/mL. The filtered water turbidity and particle counts measured during the seeding (sampling) periods (Table 2) were higher than the average concentrations over the course of each run. This effect can be seen best in the graphical run summaries (Figures 3 and 4).

General performance of the pilot filter during the course of a typical seeded run at 1 gpm/sq ft (2.5 m/h) (run 1) was characterized by a gradual decrease in both filtered water turbidity and particle counts (Figure 3). In raw water, the turbidity was 0.88 ntu, and the particle concentration was 4,581/mL. During this run, the filtered

water turbidity was less than 0.1 ntu within 20 min of the start of precoating. At 200 min into the run, the filtered water turbidity was ~0.07 ntu, the particle total was ~100/mL, and both remained at those levels through the remainder of the run. Because of the high *Cryptosporidium* removals and the correspondingly high seeding levels required, when the seed suspension was being applied the effect was apparent in the records of both filtered water turbidity and particle counts. As can be seen, when seed application reverted to normal feed, the turbidity and particle counts returned to the preseeding levels and then continued to decrease gradually with continued filtration (Figure 3).

TABLE 4 Summary of *Cryptosporidium* oocyst log reduction and filtered water turbidity levels for normal filter operation and for operation with pressure vibration

	Normal Runs		Pressure Vibration Runs	
Filtration Rate *gpm/sq ft (m/h)*	Filtered Water Turbidity *ntu*	*Cryptosporidium* Removal *log*	Filtered Water Turbidity *ntu*	*Cryptosporidium* Removal *log*
1 (2.5)	0.07	6.28	0.14	5.83
1 (2.5)	0.09	6.12	0.20	5.20
1 (2.5)	0.10	6.35	0.27	5.40
1 (2.5)			0.23	5.01
1 (2.5)			0.25	5.20
2 (5)	0.06	6.55	0.40	5.22
2 (5)	0.055	6.13	0.35	5.37
2 (5)	0.065	6.26	0.32	5.20

DE filter runs at 2 gpm/sq ft (5 m/h). Reductions in *Cryptosporidium* oocyst concentrations observed during operation at 2 gpm/sq ft (5 m/h) were higher, averaging from 6.13 and 6.55 logs (Table 3). Overall removal measured for the 2 gpm/sq ft (5 m/h) runs was 6.31 logs ± 0.22 (n = 9). Log reductions in *Cryptosporidium* oocysts observed for runs conducted at a filtration rate of 2 gpm/sq ft (5 m/h) were higher than those for runs conducted at a filtration rate of 1 gpm/sq ft (2.5 m/h) (Figure 6). A strong negative correlation was observed between filtered water turbidity and log removal, with better performance consistently at the higher filtration rate.

The apparent ability of DE filtration to provide 6 logs of removal under conditions that have proven practical in full-scale water treatment application offers a degree of control for *Cryptosporidium* not demonstrated by any other treatment process in use today, with the possible exception of membrane microfiltration.

Average turbidity levels and particle concentrations were also lower for the 2 gpm/sq ft (5 m/h) runs, although only the turbidity levels were significantly lower (t < 0.1). Performance of the pilot filter during a typical seeded run at 2 gpm/sq ft (5 m/h) (run 4), like those at 1 gpm/sq ft (2.5 m/h), showed a gradual decrease in turbidity and particle counts of the filtered water (Figure 4). The raw water turbidity was 0.7 ntu, and raw water particle concentration (total, 1.5–12.5 µm) was 4,004/mL. During this 2 gpm/sq ft (5 m/h) run, filtered water turbidity had decreased to ~0.1 ntu within 15 min of the start of precoating. At 180 min into the run, the filtered water turbidity was ~0.06 ntu, and the total particle concentration was ~100/mL. Both the turbidity and the particle counts continued to decrease slightly through the remainder of the run. The effect of applying the seed suspension was observed as a temporary increase in both filtered water turbidity and particle counts. As was seen in the 1 gpm/sq ft (2.5 m/h) runs, when seed application reverted to normal, feed turbidity and particle counts returned to preseeding levels. In Figure 5, typical head loss accumulation is illustrated for run 4.

DE filter runs at 1 and 2 gpm/sq ft (2.5 and 5 m/h) with pressure fluctuation. An independent series of seeded runs, five at 1 gpm/sq ft (2.5 m/h) and three at 2 gpm/sq ft (5 m/h), was made under conditions of pressure vibration caused by using the undamped peristaltic feed pump. Although these conditions do not resemble any condition likely to be experienced in a full-scale operating plant (using a typical centrifugal feed pump), the *Cryptosporidium* removals measured were still within the range of 5.0–5.8 logs, and the condition permitted examining the relationship between *Cryptosporidium* reductions and filtered water turbidity (Table 4). The pressure variation at the filter inlet generated using this pumping arrangement was best described as a vibration of ± 3–5 psi (±21–34 kPa), with oscillations occurring in proportion to the rotational speed of the pump (150/min at 1 gpm/sq ft [2.5 m/h] and 300/min at 2 gpm/sq ft [5 m/h]). During the run at 1 gpm/sq ft (2.5 m/h), filtered water turbidity levels ranged from 0.14 to 0.27 ntu. During the runs at 2 gpm/sq ft (5 m/h), filtered water turbidity levels ranged from 0.32 to 0.40 ntu.

Results of the testing conducted clearly confirm previously published Walton filter data suggesting potential for 6-log removal of *Cryptosporidium* oocysts in continuous DE filtration.

DISCUSSION

Results of the testing conducted as described here clearly confirm previously published Walton filter data suggesting potential for 6-log removal of *Cryptosporidium* oocysts in continuous DE filtration. Removals measured within 60–90 min of precoat initiation, using precoat of 1 kg/m^3 (20 lb/100 sq ft), were comparable to those measured more than 2 h later. Furthermore, performances observed for runs made at 2 gpm/sq ft (5 m/h) were at least as good as those measured in runs made at 1 gpm/sq ft (2.5 m/h). The average performance at 2 gpm/sq ft (5 m/h) measured in terms of *Cryptosporidium* oocyst removal, turbidity reduction, and particle removal was better than that observed at 1 gpm/sq ft (2.5 m/h), although only the difference in average turbidity reduction was significant—$t < 0.10$.

The findings of equal or better performance at 2 gpm/sq ft (5 m/h) are significant. Historically, many regulatory agencies (and consequently municipal water suppliers) have restricted operation of DE filters to 1 gpm/sq ft (2.5 m/h). The work reported here clearly indicated better performance for *Cryptosporidium* removal, along with both turbidity and particle removal, at 2 gpm/sq ft (5 m/h) than at 1 gpm/sq ft (2.5 m/h). On the basis of the work reported here and previously (Ongerth & Hutton, 1997), reconsideration of this limitation would appear to be justified and could potentially lead to a more rational consideration of DE filtration as a water treatment alternative. In addition, although this study examined filtration rates of 1 and 2 gpm/sq ft (2.5 and 5 m/h), no practical reason can be foreseen that indicates a highly effective removal of *Cryptosporidium* by DE filters would not be found at even higher filtration rates. Head loss accumulation rates are higher at higher filtration rates, which leads to shorter filter runs, but the physical facilities required are correspondingly smaller. From the data available, it is not clear whether the tradeoff between (1) higher filter loading rates with shorter filter runs to a selected pressure limit and (2) smaller equipment and capital cost would favor higher or lower filtration rates (Rees & Cain, 1990).

The economics of DE filtration have been evaluated by others and compared with other filtration alternatives, including conventional and direct granular media filtration, slow sand filtration, and membrane filtration (Troyan & Hansen, 1990). Comparisons generally show DE fil-

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tration to be competitive with other filtration alternatives, even at a filtration rate of 1 gpm/sq ft (2.5 m/h) (the limitation commonly set by state health department guidelines).

Recent attention has been focused on expressing filter performance in terms of particle removal, largely to avoid difficult and costly monitoring for *Cryptosporidium*. Although particle counting may seem easy to use and may indeed provide an efficient and useful supplement to turbidity measurements, it appears that particle counts, specifically in the 1.5–12.5-µm size range, significantly underestimate the removal of *Cryptosporidium* oocysts. The specific relationship of *Cryptosporidium* removal to 1.5–12.5-µm particle removal indeed appears to differ depending on filtration rate (Figure 7). The use of particle counting to monitor DE effluent quality must also take into account the passage of fine DE particles.

In achieving measured concentrations of *Cryptosporidium* oocysts in filtered water in which oocyst removals of about 6 logs were expected (Ongerth & Hutton, 1997), the total *Cryptosporidium* loadings to the filter were on the order of 10^8–10^9 oocysts during the testing periods, which lasted several hours. Although these levels were vastly greater than are likely to ever be experienced by water treatment plants operating normally, no evidence was found of oocysts migrating through the relatively thin filter cake. Previous work on DE filtration has shown that the pore structure of a filter cake is such that, for a filter cake with a median pore size of 7 µm, particles well below 1 µm in diameter will be removed efficiently (Cain, 1990).

In the data described here, the finding of principal interest is the clear capability of DE filtration to provide a far greater reduction in *Cryptosporidium* oocyst concentration than is provided by conventional or direct granular media filtration. The apparent ability of DE filtration to provide 6 logs of removal under conditions that have proven practical in full-scale water treatment application (operating at 1 to 2 gpm/sq ft (2.5 to 5 m/h) using DE of moderate permeability [DE-A and DE-B from the current study]) offers a degree of control for *Cryptosporidium* not demonstrated by any other treatment process in use today, with the possible exception of membrane microfiltration. Other previous work has suggested that DE filtration is capable of controlling protozoan cysts, but until the current studies, the capabilities had not been clearly defined. Several studies have suggested that DE filtration should provide a ~3-log reduction in the concentration of *Giardia* cysts (Langé et al, 1986; Logsdon et al, 1981). Similarly, other work has suggested that DE filtration should provide a greater than 3-log reduction in *Cryptosporidium* oocysts, although how much greater could not be identified (Schuler & Ghosh, 1990).

The data introduced here have benefited from advances in techniques and applications of control principles that have provided greater analytical sensitivity. Accordingly, it has been possible to directly measure *Cryptosporidium* oocyst log reductions that are greater than 6 logs. The statistical inferences that are possible with these data are entirely dependent on the quality control and the sampling design used (Figure 1). The quality of the data may also illustrate the general performance capabilities of the specific procedure used here for analysis of *Cryptosporidium* oocyst concentrations.

Taken together, the findings are highly attractive: 6 logs of *Cryptosporidium* oocyst removal, effective removal at higher filtration rates than previously accepted, and significant removal of total particles—all found for DE grades commonly used to provide economical water treatment for smaller communities. As a result, DE filtration should be seriously considered as one of the practical alternatives for treating water from sources in which *Cryptosporidium* may be present. The potential for levels of control for *Cryptosporidium* of this order of magnitude opens up a number of new possibilities for application to municipal water treatment. One possibility might be relaxing the operation of existing conventional granular media filters and using DE filters for polishing. Also, the range of community sizes for which DE filtration has historically been considered economical may be expanded considerably when DE filtration is compared with alternatives that provide equal levels of *Cryptosporidium* control.

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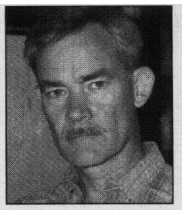

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