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Project Summary

Filtration of *Giardia* Cysts and Other Substances: Volume 2. Slow Sand Filtration

William D. Bellamy, Gary P. Silverman, and David W. Hendricks

Slow sand filtration was evaluated for a range of operating conditions and simulated ambient conditions using 1-ft-diameter laboratory filters in two phases of experimentation. The objective was to determine its effectiveness as a process in drinking water treatment for removal of *Giardia lamblia* cysts, total coliform bacteria, standard plate count bacteria, turbidity, and particles.

During Phase I experiments, three filters were operated for 16 months at hydraulic loading rates of 0.04, 0.12, and 0.40 m/hr using raw water from Horsetooth Reservoir, located adjacent to the Engineering Research Center at Colorado State University. In Phase II experiments, six filters were operated for 12 months, all at hydraulic loading rates of 0.12 m/hr, each under a different operating condition (e.g., depth of sand, size of sand, disinfection of raw water, nutrient addition, sand size, and temperature).

Phase I results showed removals of *Giardia* cysts that exceeded 99.9 percent for the three hydraulic loading rates used. The most important operating condition was the development of a biopopulation within the sand bed. Cysts removals were about 99.0 percent with new sand, but as the biopopulation matured (after about 40 weeks), removals were 100 percent, qualified by detection limits. Removals of total coliform bacteria related well to the development of the biopopulation within the sand bed, showing 90 percent removal for a new sand bed operated at 0.40 m/hr hydraulic loading rate, and 99.99 percent removal for a mature sand bed and established schmutzdecke operated at 0.04 m/hr. Removal of the schmutzdecke caused removals to decline to 99.9 percent, but recovery to 99.99 percent removal occurred within a few days.

Removals of standard plate count bacteria usually ranged from 88 to 91 percent. Because the sand bed comprising the filter develops an internal microbiological population, organisms were continuously sloughed from within the sand bed, causing significant counts of standard plate count bacteria in the effluent. Particle count removals in the size range of 6.35 to 12.7 μm ranged from 96 to 98 percent. Also because of the sloughing of material from the filter bed, significant numbers of particles occurred in the effluent. Turbidity removal was usually 27 to 40 percent. The mineral particles that made up the turbidity within the Horsetooth Reservoir consisted mostly of particles 1 μm or smaller, which passed readily through the filters.

Phase II testing was done using total coliform bacteria as the primary measure of effectiveness and periodic spiking with *Giardia* cysts. Removals of total coliform bacteria ranged from 60 percent for the filter maintained with no biological activity (e.g., chlorinated between tests) to 99.9 percent for the filter with nutrients added. Coliform removal for the control filter averaged 97 percent. Using a larger sand size (0.62 instead of 0.29 mm) caused a decline in removal rates, as did using a sand depth of 48 instead of 97 cm. Operation at 2° instead of 17°C caused

a decline in removals to 92 percent compared with 99 percent for the control filter. Removals of *Giardia* cysts were 100 percent for all tests conducted (again, qualified by detection limits).

This Project Summary was developed by EPA's Water Engineering Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

This report is the second of three volumes describing the research conducted under EPA-CSU Cooperative Agreement No. CR808650-02. The first is entitled, "Filtration of *Giardia* Cysts and Other Substances: Volume 1. Diatomaceous Earth Filtration," EPA/600/2-84/114, June 1984, and the third is entitled, "Filtration of *Giardia* Cysts and Other Substances: Volume 3. Rapid Rate Filtration," EPA/600/2-85/027, April 1985.

Objective

This report describes the results of experimental research to evaluate the effectiveness of slow sand filtration for removal of *Giardia lamblia* cysts. Other variables studied were turbidity, particles, total coliform bacteria, and standard plate count bacteria. These dependent variables were evaluated with respect to the influence of the independent variables—design and operating conditions. The research had two phases. Phase I operating conditions included hydraulic loading rate, cyst concentration, bacteria concentration, biological maturity of sand in the filter bed, age of schmutzdecke, and temperature. Phase II operating conditions included depth of sand, size of sand, temperature, disinfection of raw water, and nutrient addition to raw water.

Design and Operation of Slow Sand Filters

Slow sand filtration is a passive filtration process—that is, it is subject to very little control by an operator. The process involves no chemical addition or backwash. For recommended design, effective sand size ranges from 0.15 to 0.35 mm, with a uniformity coefficient of less than 2. The sand bed depth ranges from 60 to 120 cm and is supported by graded gravel 30 to 50 cm deep. Drain tiles are placed at the bottom of the gravel support to collect the filtered water. Hydraulic loading rates range from 0.04 to 0.40 m/hr.

During operation of the slow sand filter, biological growth occurs within the sand bed and the gravel support. Also, a layer of inert deposits and biological material called the schmutzdecke forms on the surface of the sand bed. In the literature, the effectiveness of slow sand filtration is attributed mostly to the role of the schmutzdecke, but this research has found that both the schmutzdecke and the biological growth within the sand bed have important roles in the effectiveness of slow sand filtration. The latter may require weeks or months to develop, depending on the nutrients within the raw water.

Operation of a slow sand filter requires two periodic tasks: (1) cleaning by removal of the schmutzdecke, and (2) replacing of the sand. Schmutzdecke is removed when the headloss exceeds the designed value, which may range from 1 to 2 m. After draining the filter, the schmutzdecke is removed by scraping about 2 cm from the surface of the sand bed. The removal interval depends on the rate of accumulation of material, which in turn is related to the contaminants present in the raw water and the hydraulic loading rate. Since operating expenses are affected by the frequency of schmutzdecke removal, pilot testing is advisable to determine this important operating parameter. Replacing sand is necessary after repetititve scrapings have reduced the sand bed in the filter to its lowest acceptable depth.

A number of slow sand filtration treatment plants have been built in the United States, but most were completed in the first decades of the century. Today the technology is well established in Europe, though it never gained a firm foothold in the United States. The process seems well suited to small communities that need a technology less complex than rapid sand filtration.

Experimental Apparatus and Methods

Apparatus

The Phase I experimentation was conducted using three 1-ft-diameter pilot plant units operated in parallel. The filters were packed with 96 cm of sand (d_{10} = 0.28 mm, d_{60} = 0.41 mm) supported by 46 cm of coarse sand and gravel. The effluent was routed through a 241-mm, 5-μm-pore-size membrane filter for *Giardia* sampling, or it could flow directly to the constant head discharge device. For temperature control, the filters were equipped with cooling coils in the heads, and the filter feed tank had a built-in temperature control. Temperatures were maintained constant throughout the system within the range 3° to 17°C.

Six slow sand filter columns were used in Phase II arranged in a circular configuration about an operating platform. The constant head tank in the center distributed equal flow to each filter by means of orifices. The six columns were operated continuously for a 12-month period.

The effluent flow could be directed through the constant head outflow device or through a 142-mm membrane filter used for *Giardia* sampling. A cooling element was used for two filters to maintain temperatures at 5° and 2°C. The feed water to the six filters was maintained at 17°C by means of cooling and heating elements located in a 1200-L feed tank.

Operation

The three slow sand filters in Phase I were operated continuously from August 1981 to December 1982 at hydraulic loading rates of 0.04, 0.12, and 0.40 m/hr filters designated 1, 2, and 3, respectively. The common feed tank delivered the same influent to each of the slow sand filters, thus allowing for the evaluation of process response to different hydraulic loading rates.

The other operating variables studied were (1) temperature, (2) influent bacteria concentration and cyst concentration, (3) age of the schmutzdecke, and (4) biological maturity of the sand in the filter bed. These variables were changed systematically to determine their effect on removals of *Giardia* cysts, bacteria, turbidity, and particles.

Temperature effects were examined by operating the system at 5° and 15°C. The highest temperature permitted during *Giardia* testing was 15°C. This upper limit was based on observation that the cysts deteriorate at higher temperatures.

Giardia cyst concentrations were varied between 50 and 5,075 cysts/L. Because the filtration removal processes were highly effective, high influent cyst concentrations were necessary to ensure passage of a few cysts through the filter. The high cyst concentration also permitted discernment of possible functional relationships and encompassed the highest expected ambient concentration, which was estimated as 500 cysts/L.

Total coliform bacteria ranged from almost 0 to about 300,000/100 ml. These latter levels were the result of adding primary settled sewage to the filter feed

tank and from fecal residue accompanying *Giardia* cyst addition. No attempt was made to change these concentrations systematically. The bacteria were added to challenge the filter, since the raw water bacteria counts were normally quite low.

The effect of the schmutzdecke was determined by testing after it had been allowed to develop and immediately after scraping. A developed schmutzdecke is defined as one that has had at least 2 weeks to establish itself.

The biological maturity of the sand bed indicates the degree of microbiological development throughout its depth. This condition is not measurable, but is a function of the number of weeks of undisturbed filter operation. To determine the influence of microbiological maturity, testing was done for three filter conditions: (1) new sand bed and new gravel support (which simulated start up of a new filter); (2) new sand bed with microbiologically mature gravel support (which simulated a filter that had just had its sand totally replaced); and (3) sand bed and gravel support that are both microbiologically mature (which simulated steady-state operation). Testing under the third condition was done at various filter ages, ranging from 26 to 80 weeks. The age of the filter can be used as an index of microbiological maturity for given raw water conditions. The most pertinent conditions that affect the length of time to bed maturity are nutrient availability and temperature.

A test run consisted of filling the batch feed tank with lake water and then spiking the water in the tank with a known concentration of *Giardia* cysts. When additional coliforms were desired, the tank was also spiked with primary settled sewage. The feed tank was then sampled for *Giardia* cysts, total coliform bacteria, standard plate count bacteria, particles, and turbidity. The same sampling and analyses were performed on the three filter effluents the following day to allow for the needed volume displacement within the filter column. This procedure (i.e., spiking, sampling of the feed tank, and sampling of the filter effluents) was continued daily for 3 to 11 days, depending on the particular test run.

The six pilot filters in Phase II were operated in parallel with a common raw water source. Filter No. 1 was operated as the control, providing a basis for comparison with the other filters. Each of the other columns was operated with one of the process variables having a different magnitude than did the control.

With the six filters, three levels of biological activity were studied along with three other variables—sand bed depth, sand size, and temperature. Filter 1, the control, had the amount of biological development that would typically occur with the Horsetooth Reservoir water. Filter 3 was subjected to 5 mg/L residual chlorine between runs to minimize biological growth. Sterile synthetic sewage was added to Filter 4 to promote additional biological growth within the sand bed. Filter 2 had a 48-cm sand bed depth (instead of the 97 cm of the other filters). Filter 5 was packed with sand having d_{10} size 0.615 mm (instead of the 0.287-mm size in the other filters). Filters 5 and 6 were operated at 5°C continuously (instead of at the 17°C of the other filters).

To evaluate the effects of process variables, the filters were spiked with a laboratory culture of total coliform bacteria. Filter No. 3, which was disinfected by a sodium hypochlorate solution, was purged of disinfectant with sodium thiosulfate before such tests. Effluent samples from the six filters were obtained once each day during the test period. This series of measurements, together with the spiking, constituted a test run. Such test runs were conducted at various times, usually weekly, throughout the 11-month period of continuous filter operation. In addition to the total coliform testing, removals of turbidity and standard plate count bacteria were monitored routinely. Tests with *Giardia* cysts, concentrated from dog feces, were conducted on a more limited basis to minimize the fouling of the sand surface caused by debris and fats present in the *Giardia* cyst concentrate.

Results

Phase I Removals

Table 1 summarizes the removals from Phase I averaged for all data over the period August 1981 to December 1982 for the three filter columns operated at 0.04, 0.12, and 0.40 m/hr. The number of samples obtained for each variable and the range of each are included.

The data showed uniformly high removals for all dependent variables except turbidity, which ranged from 27 to 39 percent for raw water turbidities ranging from 2.7 to 11 NTU. These turbidity removals are not as high as reported by others (e.g., the Kassler plant in Denver) because of the small clay particles that make up the suspended matter in the raw water source, Horsetooth Reservoir. About 30 percent of the turbidity in this water will pass through a 0.45-μm membrane filter.

Removals of *Giardia* cysts, total coliforms, and fecal coliforms were all high. At optimum conditions of operation, effluent concentrations of each approached their respective detection limits.

Hydraulic Loading Rate

Well-defined relationships can be seen from the data in Table 1, in which removals of coliform bacteria, standard plate count bacteria, *Giardia* cysts, and turbidity decline with increasing hydraulic loading rate. For example, average re-

Table 1. Average Percent Removals for Dependent Variables in Slow Sand Filter Columns

Dependent Variable	Total Number of Analyses	Range of Variable in Raw Water	Percent Removal of Parameter: Filter 1 v = 0.04 m/hr	Filter 2 v = 0.12 m/hr	Filter 3 v = 0.40 m/hr
Giardia *cysts*	222	50-5,075 cysts/liter	99.991	99.994	99.981
Total coliforms	243	0-290,000 coliforms/100 ml	99.96	99.67	98.98
Fecal coliforms	81	0-35,000 coliforms/100 ml	99.84	98.45	98.65
Standard plate count	351	10-1,010,000 organisms/ml	91.40	89.47	87.99
Turbidity	891	2.7-11 NTU	39.18	32.14	27.24
Particles (6.35-12.7 μm)	39	62-40,506 particles/10 ml	96.81	98.50	98.02

movals of total coliform bacteria declined from 99.991 percent at 0.04 m/hr to 99.981 percent at 0.12 m/hr. Though hydraulic loading rate has an influence on filtration efficiency, the effect is not great enough to warrant establishing a firm design criterion for this parameter. Rather, the concern should be with respect to economic aspects. For example, the advantage of reduced construction costs for a design with a high hydraulic loading rate must be weighed against increased operating costs caused by the need for more frequent schmutzdecke removals. Performance would be only slightly poorer at the higher hydraulic loading rate.

Microbiological Conditions

The biological conditions governing the process effectiveness of the filter are: (1) the degree of schmutzdecke formation; and (2) the microbiological maturity of the sand bed. Figure 1 illustrates how these conditions affect coliform effluent concentrations (i.e., the percent remaining at hydraulic loading rates of 0.04, 0.12, and 0.40 m/hr). Also, each of the bars shows effluent coliform concentrations calculated from a hypothetical influent density of 1 million coliforms per 100 ml. These figures are derived from the percent remaining data and permit a more tangible means for comparing results in terms of whole numbers.

To evaluate the respective roles of the schmutzdecke and the maturity of the sand bed, it is useful to examine first a filter column with a new sand bed, including a new, graded gravel support. This simulates a newly constructed filter during startup when there is no biological development in the sand bed and no schmutzdecke. For this condition of new sand (as indicated in Figure 1 for Run 118), 15.4 percent coliforms remained, or 154,000 coliforms/100 ml remained from a hypothetical 1 million coliforms/100 ml in the influent. In other words, filtration through the new sand will cause an order of magnitude reduction.

In contrast to the initial startup of a filter is the filter that has been in operation for a period of time and has a mature biological population and an established schmutzdecke. Such a case is represented by runs 104, 105, and 106, which show that a mature filter will reduce the coliform concentration by 2.5 to 4 logs, or from 1 million coliforms/100 ml to 40, 1000, and 4000 coliforms/100 ml, respectively.

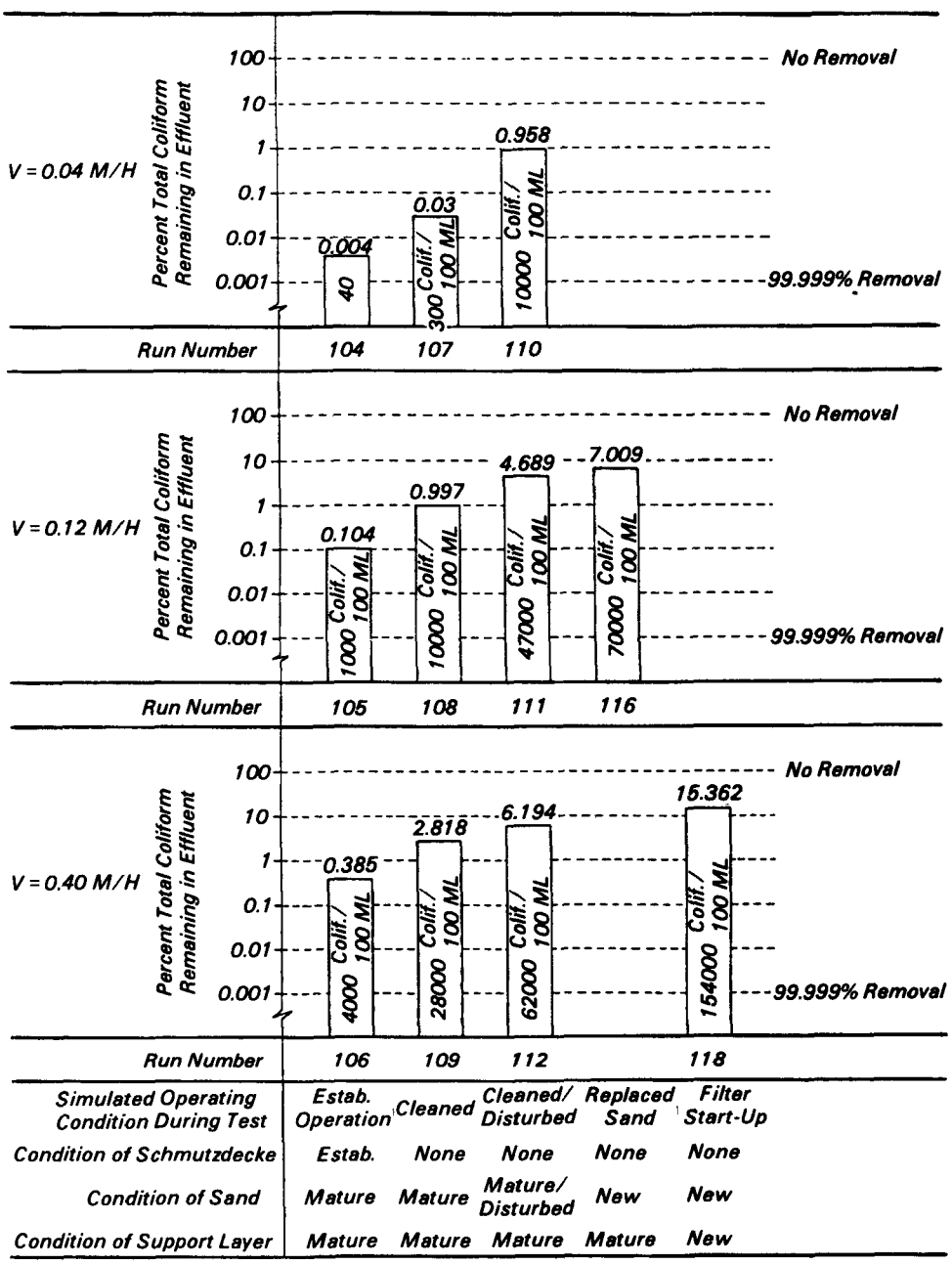

Figure 1. Effect of schmutzdecke and sand bed conditions on percent of remaining total coliforms for three hydraulic loading rates.

Schmutzdecke removal will result in approximately a 1-log decrease in treatment efficiency when compared with operation under established conditions. This result can be demonstrated by comparing runs 107, 108, and 109 (at 300, 10,000, and 28,000 coliforms/100 ml, respectively) with runs 104, 105, and 106 (at 40, 1000, and 4000 coliforms/100 ml, respectively).

Replacing sand will result in almost a 2-log decrease in treatment efficiency. Run 116 shows 70,000 coliforms/100 ml remaining, compared with only 1000 coliforms/100 ml for the established condition represented by run 105.

One additional condition tested was the effect of removing the schmutzdecke and then disturbing the sand bed, as illustrated by runs 110, 111, and 112. This experiment was intended to simulate the effects of a full-scale filter operation in which the filter is drained and the sand bed is disturbed by the movement of men

and equipment over the filter surface during cleaning. The experimental disturbance was accomplished for each filter by draining the filter for a 2-day period, removing the schmutzdecke, mixing the top 10 cm of sand, and pounding on the sand surface. This experiment caused an additional 0.5- to 1-log decrease in treatment efficiency compared with the filter cleaning procedure when no disruption occurred.

The test results as shown in Figure 1 confirm the importance of the role of microbiological conditions in the treatment effectiveness of slow sand filtration. The best treatment can be expected from a filter that has been in operation for an extended period of time. This filter will have a mature biopopulation within the filter bed and will have an established schmutzdecke. The treatment efficiency will deteriorate markedly as greater portions of the biological community are disrupted as shown in Figure 1.

The data in Table 2 show the effects of the various filter operating conditions on removals of *Giardia* cysts. The first two rows compare removals of *Giardia* cysts between a control filter and one that has new sand and new gravel support. No cysts were detected in the effluent of the control filter, and only 17 cysts/L were found in the effluent of the new media filter. This result demonstrates that a filter with a mature biological population can remove cysts to the detectable limit, and that even a new filter removes 99 percent of the influent cysts. Both filters were subjected to an influent cyst concentration of 2000 cysts/L.

Results for a similar experiment with a new sand bed and a mature gravel support (Run 116) showed zero cysts/L in the effluent, compared with an influent cyst concentration of 3692 cysts/L. This result indicates that even a modest amount of microbiological growth in the sand bed, or indeed in the gravel support, can provide the marginal effect needed to cause removal of influent cysts to levels below the detection limit.

The third secton of Table 2 presents the results of 15 *Giardia* removal test runs on filters with freshly scraped sand surfaces (i.e., no schmutzdecke development). These test runs were arranged chronologically according to continuous filter operation, ranging from 26 to 70 weeks. Table 2 shows that removal of *Giardia* cysts to below the detection limit was achieved in all but four of these test runs. The key difference between those tests that achieved nearly complete removal and those that did not was the degree of microbiological maturity within the sand bed. All four of the tests in which cysts were passed occurred during the first 41 weeks of filter operation, indicating that when the microbiological population has developed to maturity, complete removal of *Giardia* cysts can be expected. As demonstrated in Table 2, this result occurs independently of hydraulic loading rate, influent *Giardia* cyst concentration, and presence of a schmutzdecke.

The same improvement in *Giardia* cyst removal with time is demonstrated by results shown in the fourth part of Table 2, where the test data are summarized in chronological order for 24 *Giardia* tests with filters having established schmutzdeckes. These results show that the removal of cysts improved steadily with time and was independent of schumtzdecke age. Cysts were passed through filters with 12-week-old schmutzdeckes, whereas they were removed below the detectable limit with 4- to 5-week-old schmutzdeckes when the microbiological population within the filter was given a longer time to mature. In fact, after 49 weeks of operation, cyst removal below detection limit was achieved in all cases, even when influent cyst concentrations as high as 5075 cysts/L. These results demonstrate that the age of the schmutzdecke is not as important for *Giardia* cyst removal as the maturity of the microbiological population throughout the sand bed and gravel support.

Phase II Removals

Design—

Phase II testing was designed to ascertain the effects of sand size, sand bed depth, and sustained low temperatures on removals of *Giardia* cysts and other parameters. No experiments to determine removals of *Giardia* cysts were done with the chlorinated filter and the nutrients-added filter, to avoid the influence of such testing on their performance (e.g., the influence of nutrients and debris).

The results of the Phase II *Giardia* removal tests demonstrated that removal was not affected by increasing the effective sand size to 0.615 mm, by continuous operation at 5°C, or by reducing the sand bed depth to 0.48 m. Each of the filters (1, 2, 5, and 6) had a mature biological population and the same influent water, and each was operated at hydraulic loading rates of 0.12 m/hr. Cysts were not detected in any of the effluent samples.

To induce cyst breakthrough, another filter column was newly packed with 0.615 mm sand, operated at 0.47 m/hr, and then challenged during the first 2 days of operation with 2770 cysts/L. This test resulted in passage of 26 cysts/L through the filter. Even under these extreme conditions, removal was 99 percent. Testing with new sand was also carried out during rapid sand experimentation, which was the subject of Volume 3 of this study. Testing with 0.43 mm sand at hydraulic loading rates in excess of 14 m/hr and without chemical addition resulted in four of eight test runs with removals of less than 50 percent.

Effects of Process Variables on Filter Performance in Phase II—

The effects of process variables on filter performance were evaluated by using the percent removals of total coliform bacteria as the measure of efficiency. Removals of standard plate count bacteria and turbidity were determined also, but they were not suitable for this purpose because heterotrophic bacteria were shed by the filter as a result of internal growth, and turbidity removal from Horsetooth Reservoir water had little relation to operation because of its unique and nonrepresentative behavior, as reported in the Phase I results.

Biological Community—Phase II investigations were designed to study the effects of low, natural, and accelerated biological activity on filter performance, as represented by Filters 3, 1, and 4, respectively. For low biological activity, growth was prevented in Filter 3 by maintaining a 5-mg/L chlorine residual between test runs and dechlorinating with sodium thiosulfate a test run. Augmented biological activity was created in Filter 4 by continuously adding sterile synthetic sewage to the filter. Filter 1 was a control filter that used raw water from Horsetooth Reservoir with no alteration; this filter represented the natural condition.

The results of the Phase II testing demonstrated that as the activity of the biological community increased from minimal biological community for the chlorinated filter to augmented activity for the nutrients-added filter, the removals of coliforms, standard plate count bacteria, and turbidity increased significantly. For Filters 3, 1, and 4, removals were 60, 98, and 99.9 percent for total coliform bacteria; -89, -41, and 58 percent for standard plate count bacteria; and 5, 15, and 52 percent for turbidity. These results demonstrate the unmistakable influence of biological activity on filter performance.

Temperature—Decreasing the temperature from 17° to 5° or 2°C decreased

Table 2. *Effect of Operating Conditions on* Giardia *Cyst Removal by Slow Sand Filtration*

Test Objective	Condition of Sand Bed and Gravel Suport	Age of Schmutz-decke (Weeks)	Length of Time of Operation (Weeks)	Run Number	Filtration Rate (m/hr)	Influent Cyst Conc. (cyst/liter)	Effluent Cyst Conc. (cyst/liter)	Percent Removal (%)	Detection Limit (cyst/liter)	Effluent Volume Sampled (liter)*
Effect of New Sand Bed and New Gravel Support	New Sand Bed/ New Gravel Support	0	0/0	118	0.40	2000	17.05	99.15	0.046	610
	Control Filter: (Mature Sand Bed/Mature Gravel Support)	10	80	119	0.40	2000	0.0	100	0.049	770
	New Sand Bed/ Mature Gravel Support	0	0/67	116	0.12	3692	0.0	100	0.039	497
Effect of New Sand Bed	Control Filter: (Mature Sand Bed/Mature Gravel Support)	4	67	117	0.12	3692	0.0	100	0.40	566
Effect of Schmutz-decke Removal	Mature Sand Bed/ Mature Gravel Support	0	26	48	0.040	420	2.014	99.520	0.085	65
		0	26	49	0.40	420	5.431	98.707	0.020	270
		0	33	47	0.12	420	1.541	99.633	0.030	180
		0	41	75	0.04	50	0.0	100	0.036	314
		0	41	76	0.40	50	0.002	99.996	0.005	2239
		0	45	81	0.04	50	0.0	100	0.104	344
		0	45	82	0.40	50	0.0	100	0.042	2671
		0	48	74	0.12	50	0.0	100	0.014	803
		0	52	80	0.12	50	0.0	100	0.013	853
		0	62	107	0.04	1500	0.0	100	0.302	142
		0	62	109	0.40	1500	0.0	100	0.036	1199
		0	63	110+	0.04	1953	0.0	100	0.151	176
		0	63	112+	0.40	1953	0.0	100	0.026	1020
		0	69	108	0.12	1500	0.0	100	0.121	354
		0	70	111+	0.12	1953	0.0	100	0.059	454
		3	29	54	0.04	500	0.243	99.949	0.061	84
		3	29	55	0.40	500	0.321	99.936	0.015	346
		5	31	60	0.04	500	0.0	100	0.062	81
		5	31	61	0.40	500	0.111	99.978	0.014	366
		3	36	53	0.12	500	0.116	99.977	0.023	223
		5	38	59	0.12	500	0.035	99.993	0.023	220
		11	38	66	0.04	50	0.050	99.900	0.040	175
		2	38	67	0.40	50	0.011	99.978	0.006	1098
		12	39	69	0.04	50	0.114	99.772	0.037	140
		3	39	70	0.40	50	0.017	99.966	0.005	762
Effect of Established Schmutz-decke	Mature Sand Bed/ Mature Gravel Support	11	45	65	0.12	50	0.016	99.968	0.016	429
		12	46	68	0.12	50	0.041	99.918	0.015	345
		4	49	87	0.04	1000	0.0	100	0.993	111
		4	49	88	0.40	1000	1.373	99.863	0.127	871
		5	50	90	0.04	1000	0.0	100	0.586	157
		5	50	91	0.40	1000	0.0	100	0.109	843
		4	56	86	0.12	1000	0.0	100	0.398	277
		5	57	89	0.12	1000	0.0	100	0.246	374
		16	60	101	0.04	1087	0.0	100	0.200	138
		16	60	103	0.40	1087	0.0	100	0.024	1134
		17	61	104	0.04	5075	0.0	100	0.231	171
		17	61	106	0.40	5075	0.0	100	0.027	1440
		16	67	102	0.12	1087	0.0	100	0.081	342
		17	68	105	0.12	5075	0.0	100	0.091	435

** This is the effluent volume that has been concentrated by a 5-µm polycarbonate membrane filter.*

+ The entire filter bed was disrupted during the schmutzdecke removal process in an attempt to simulate full-scale procedures.

removals of coliform bacteria and standard plate count bacteria from about 99 percent nominally to 90 percent nominally for each. The filtration efficiency was not reduced as sharply as expected. The literature has reported sharp reductions in percent removals as a result of lower temperatures.

Sand Bed Depth—The removals of total coliform bacteria were 97 percent at a sand bed depth of 1 m and 95 percent at 0.5 m. This result indicates that bacterial removal is not overly sensitive to sand bed depths above 0.5 m. In practice, this result means that a series of schmutzdecke removals with the resulting attrition of the sand bed from 1 m to 0.5 m will not seriously impair the efficiency of the filtration process.

Sand Size—To discern better the role of effective sand size, three filters were packed with sand with effective sizes of 0.62, 0.28, and 0.13 mm. Eighteen test runs using pure cultures of total coliform bacteria were then conducted parallel with each filter. Each of these filters had a mature biological population. The coliform removal improved from 96.0 to 98.6 to 99.4 percent for effective sand sizes of 0.615, 0.278, and 0128 mm, respectively.

Summary of Results

Findings from the experimental program are summarized first in terms of the overall removal effectiveness of slow sand filtration for the parameters tested, and second in terms of the effects of operating conditions. The effectiveness of slow sand filtration for removing the parameters tested is summarized as follows:

1. *Giardia* cyst removal exceeded 98 percent for all operating conditions tested. Once a microbiological population is established within the sand bed, removal will be virtually 100 percent.
2. Coliform removals exceeded 99 percent on the average over all operating conditions. Even with new sand, coliform removals were 85 percent.
3. Removals of standard plate count bacteria and particles range from 88 to 91 percent and from 96 to 98 percent, respectively.
4. Turbidity removals averaged from 27 to 39 percent. This low removal was caused by the fine clay turbidity particles characteristic of the lake water used in the testing program.

Operating conditions affected removals of *Giardia* cysts, total coliforms, and standard plate count bacteria in the following ways:

1. *Hydraulic loading rate.* Removals of *Giardia* cysts, coliform bacteria, standard plate count bacteria, and turbidity declined with increasing hydraulic loading rate. However, even at 0.40 m/hr, removals of *Giardia* cysts and coliform bacteria were high—99.98 percent and 99.01 percent, respectively.
2. *Temperature*—The Phase II experiments for mature filters showed that *Giardia* removals were uniformly 100 percent for continuous operation at both 17° and at 5°C. However, removals of total coliform bacteria declined from 97 percent at 17°C to 87 percent at 5°C. Effluent concentrations of standard plate count bacteria were 100 times higher at 2°C than at 5°C.
3. *Influent concentration of bacteria and* Giardia *cysts.* Effluent concentrations of coliform bacteria and standard plate count bacteria increased with increasing influent concentrations. At the same time, removals increased. A similar relation would be expected for removals of *Giardia* cysts, but data were not sufficient to establish it. Though this information may be of academic interest, removals of the above are influenced more strongly by the microbiological maturity of the sand bed than by influent concentrations.
4. *Conditions of the sand bed.* A new sand bed removed 85 percent of influent coliform bacteria and 98 percent of influent *Giardia* cysts. As the sand bed mature biologically, removals improved to greater than 99 percent for coliform bacteria and virtually 100 percent for *Giardia* cysts. Disturbance of the sand bed caused reduced coliform removals, but it had no effect on *Giardia* cyst removals. Development of the schmutzdecke further improved removals of coliform bacteria by an order of magnitude. The presence or absence of a schmutzdecke has essentially no influence on *Giardia* cyst removal efficiency. The microbiological maturity of the sand bed is the most important variable in removal of *Giardia* cysts and coliform bacteria. This mature condition develops over a matter of weeks or months, depending on raw water conditions.
5. *Sand Bed Depth*—Coliform removals averaged 97 percent for the control filter with a bed depth of 1.0 m and declined only to 95 percent for the filter with a bed depth of 0.5 m. These results demonstrate that the bed depth can be reduced to 0.5 m by repeated schmutzdecke removals without significant impairment of filtration removal efficiency.
6. *Sand Size*—Removals of *Giardia* cysts were 100 percent for all sand sizes tested. Removals of total coliform bacteria declined from 99.4 percent for 0.128-mm sand to 96.0 percent for 0.615-mm sand. Though results showed that sand size had a functional influence on bacteria removals, the removals were high even with the 0.615-mm sand. So the argument for using smaller sand is not strong from the standpoint of removal effectiveness. Instead, the argument for using an effective sand size of about 0.35 mm is economic. The schmutzdecke will penetrate to a greater depth with larger sand, necessitating removal of more sand during schmutzdecke removal and resulting in higher operating costs. Thus using the smaller sand size is preferable when the choice is economically favorable and if the trade off in higher headloss is not appreciable.
7. *Biological Activity*—Phase II results showed that the average coliform removals for Filter 3, which was chlorinated between test runs and had no biological community, were only 60 percent. For the control filter, the average coliform removal was 98 percent. Filter 4, which had nutrients added, showed an average coliform removal of 99.9 percent. These results augment those of Phase I and establish unequivocally the importance of the biological community and its level of activity within the sand bed.

Conclusions

Slow sand filtration is an effective water treatment technology as determined by removals of total coliform bacteria and *Giardia* cysts. Furthermore, the process is passive in nature, requiring little action on the part of the operator. This technology should be considered as an alternative when water treatment systems are being selected. Pilot plant testing should be done, however, to determine the technical feasibility of each alternative.

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The selection should be made by economic analysis and judgments of how appropriate the technologies are in terms of community attitudes toward operation.

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William D. Bellamy is presently with CH2M-Hill Consulting Engineers, Newport Beach, CA 92660; the EPA author ***Gary P. Silverman*** *is with the U.S. Environmental Protection Agency, San Francisco, CA 94105; and David W. Hendricks is with Colorado State University, Fort Collins, CO 80523.*
Gary S. Logsdon *is the EPA Project Officer (see below).*
The complete report, entitled "Filtration of Giardia *Cysts and Other Substances: Volume 2. Slow Sand Filtration," (Order No. PB 85-191 633/AS; Cost: $26.50, subject to change) will be available only from:*
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: 703-487-4650
The EPA Project Officer can be contacted at:
Water Engineering Research Laboratory
U.S. Environmental Protection Agency
Cincinnati, OH 45268

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