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COMPARISON OF SOME FILTRATION PROCESSES APPROPRIATE FOR GIARDIA CYST REMOVAL

by

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16. ABSTRACT

Slow sand filtration, diatomaceous earth (DE) filtration, and coagulation-filtration (including conventional treatment, direct filtration, and in-line filtration), have been evaluated for Giardia cyst removal at pilot plant and/or field scale. Properly designed and operated, the above process can attain 99 percent cyst reductions, or higher. This paper discusses relative advantages and disadvantages of the proceses, and factors that may result in success or failure of treatment. Slow sand filtration is the least complicated process from the operator's perspective. It may be the most appropriate for small systems if the raw water is treatable. It very effectively removes viruses, bacteria, and cysts; but it is not very effective for removal of THM precursor organic chemicals. It gives the operator the least ability to change treatment in response to changes in raw water. DE filtration is very effective for cyst removal, but removal of very small particles requires use of fine grades of DE or chemical preconditioning of DE. Process modifications can yield iron and manganese removal. THM precursor removal is small. Operator skills required are mostly of a mechanical nature. Coagulation-filtration has the greatest flexibility, and can remove 30 to 50% of THM precursor; also turbidity, microorganisms, and metals that can be precipitated before filtration. Many factors influence process performance so a good understanding of coagulation chemistry is needed for most effective operation regardless of plant size. This requires the greatest level of operator ability for continued, dependable performance. Process variations include conventional treatment, direct filtration, and in-line filtration.

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COMPARISON OF SOME FILTRATION PROCESSES APPROPRIATE FOR GIARDIA CYST REMOVAL

Gary S. Logsdon*

INTRODUCTION

Waterborne giardiasis outbreaks have been occurring in the USA for the past two decades, and continue to occur. This suggests a need for better water treatment. Disinfection provides a barrier for waterborne transmission of Giardia cysts. Craun (1986) reported that 19,770 cases of waterborne giardiasis were related to deficiencies in treatment of surface water sources by community water systems from 1965 through 1984. Of these, 61% were related to failures to adequately disinfect in systems having disinfection as the only treatment. Another barrier is effective filtration. This paper reviews filtration studies at pilot scale or full scale, or both, and compares performance capabilities and advantages of slow sand filtration, diatomaceous earth (DE) filtration, and coagulation-filtration. The latter category includes conventional filtration (coagulant feed and rapid mix, flocculation, sedimentation, and filtration), direct filtration (coagulant feed and rapid mix, flocculation, and filtration), and in-line filtration (coagulant feed and rapid mix, followed by filtration).

All of the above filtration processes, if they are properly designed and operated, and if they are treating a source water of suitable quality, can reduce the concentration of Giardia cysts by 99 percent or more. Filtration failures can occur because of improper design or operation, or because a given process is not appropriate for the raw water being treated. Of the

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19,770 cases of giardiasis mentioned above, 38% occurred because of failures in filtration. Aspects of filter plant design and operation are discussed in subsequent sections of this paper. The relative costs of the processes are not discussed because these would be influenced by conditions that are site specific; thus general comparisons would be of limited usefulness.

SLOW SAND FILTRATION

Slow sand filtration studies have been supported in recent years by the U.S. Environmental Protection Agency, the American Water Works Association Research Foundation, and the State of Utah, among others. Some parameters in EPA funded studies are given in Table 1. Filters have been evaluated for ability to remove *Giardia* cysts, bacteria, turbidity, particles, and trihalomethane (THM) precursor.

Slow sand filters have been shown capable of removing 99 to 99.99 percent of the raw *Giardia* cysts in water (Bellamy *et al*. 1985 a, 1985 b; Pyper, 1985). Using pilot filters Bellamy *et al*. (1985 a) found that cyst removal did not deteriorate after filter scraping. Pyper (1985) observed that at 7.5°C to 21°C, cyst removal was 99.98% to 99.99%. At 0.5°C to 0.75°C, removal ranged from 99.36% to 99.91%; however, at 0.5°C, cyst removal deteriorated to 93.7% when both *Giardia* cysts and primary unchlorinated sewage effluent were added to the raw water simultaneously. In this situation, the loading of organisms in the influent water may have been greater than the established biological population of the slow sand filter could cope with.

Total coliform removal was found to be adversely influenced by increases in filtration rate from 0.04 to 0.4 m/hr (Bellamy *et al*., 1985 a), by decreases in filter bed depth from 0.97 m to 0.48 m (Bellamy *et al*., 1985 b), by increases in sand size from 0.13 mm to 0.61 mm (Bellamy *et al*., 1985 b), and by decreases in temperature from 17°C to 2°C (Bellamy et al., 1985 b). Of these parameters, the 0.61 mm sand size would be greater than sizes typically used and might have accentuated the adverse impact of that variable. The use of 0.61 mm sand resulted in average total coliform removal of 96% vs. 99.4% for 0.13 mm sand. Temperature decreases from 17°C to 5°C or 2°C resulted in deterioration in coliform removal from the 99% level to about 90% for the colder waters. Cleasby et al. (1984 a) found that total coliform removal was lower during the first two days after scraping than during the remainder of the run. In some instances, differences in the two time periods were slight, but 5 of 9 runs exhibited coliform removals ranging from 82% to 95% during the first two days. During the remainder of the runs, removals ranged from 97% to 100%. Cullen and Letterman (1985) in most cases did not observe any effects of scraping (a ripening period) in total coliform data collected in a study of seven operating slow sand filter plants in the State of New York.

Virus removal has been reported (Taylor, No Date) to be influenced by temperature and filtration rate. At 0.20 m/hr and 11° to 12°C, removal was 99.9999% vs. 99.8% for 0.40 m/hr and 6°C. In another set of experiments, Taylor reported 99.8% removal at 0.20 m/hr but only 91% at 0.40 m/hr.

Researchers have observed variation in the ability of slow sand filters to reduce turbidity to the 1 Nephelometric Turbidity Unit (NTU) Maximum Contaminant Level (MCL) specified in the U.S. Environmental Protection Agency's Drinking Water Regulations. Fox et al. (1984) found that when water from a gravel pit in southwestern Ohio was filtered at 0.12 m/hr, after an initial ripening period had allowed the biopopulation to become established on new sand, the 1 NTU MCL was always met. Raw water turbidity ranged from 0.2 to 10 NTU. Cleasby et al. (1984 a) reported that after the first two runs, typical effluent turbidity was 0.1 NTU except during the first two days after scraping. Water for that research came from a gravel pit in central Iowa, with turbidity ranging from <1 to 30 NTU. Pyper observed slow sand filtered water turbidity of 0.1 NTU or less for 50% of the time, and 1.0 NTU or less for 99% of the time in McIndoe Falls, Vt. The source of water was Coburn Pond, a body of open water with an open water surface area of about 4 hectares, plus about 20 hectares of wetland. Raw water turbidity ranged from 0.4 to 4.6 NTU and color averaged 24 C.U. In contrast with these results, when Horsetooth Reservoir was treated (Bellamy <u>et al</u>. 1985 a, 1985 b), the filtered water turbidity ranged from 3 NTU to 5 NTU, and the 1 NTU MCL was not met. Raw water turbidity of Horsetooth Reservoir generally was 6 NTU to 8 NTU. Slezak and Sims (1984) reported that about 15% of 27 plants surveyed produced filtered water with an average turbidity of 1.0 NTU or higher, whereas turbidity averaged 0.4 NTU or lower at half of the plants.

The different degrees of turbidity reduction in some cases may be attributed to the nutrient condition of the filters. Water collected high in the Rocky Mountains and transported to Horsetooth Reservoir would not be expected to be high in nutrients for growth of biopopulation in filters. Bellamy <u>et al</u>. (1985 b) reported adding sterile nutrient (BOD about 4 mg/L) to one test filter, which should have increased the biopopulation in the filter. Under parallel operation, turbidity reduction averaged 52% from this filter vs. 15% from the filter treating unaltered Horsetooth Reservoir water. Pavoni <u>et al</u>. (1972) reported that exocellular polymers produced by bacteria in an activated sludge culture were capable of flocculating Kaolinite suspensions and promoting settling. It appears possible that the biological population of a slow sand filter may produce exocellular polymers that enhance the "stickiness" of filter media and inorganic particles in the slow sand filter, thus improving the filter's capability to remove such particles. The surface waters tested in Iowa and Ohio contained sufficient nutrient to support algae during the summer, and the water in Vermont would be expected to be high in nutrients resulting from decaying vegetation in the wetlands. Thus, we would infer that those waters had higher nutrient levels than the Horsetooth Reservoir water.

Slow sand filters should not be expected to remove large amounts of THM precursor unless something has been done to chemically alter the precursor before filtration. Humic materials, although in contact with microorganisms in nature, seem to persist in the environment. The biopopulation in the Vermont slow sand filter removed about 10% of the trihalomethane formation potential (THM FP) that was between 100 µg/L and 200 µg/L in raw water. Fox et al. (1984) reported TOC removal of 19% and THM FP removal of 18% when treating southwestern Ohio gravel pit water.

In the research at Iowa State (Cleasby, 1984 b), algae were encountered and evaluated for removal and influence on filter efficiency. Chlorophyll-a measurements were less than 5 µg/L during the winter and spring of 1981-1982, until mid-April, increasing to nearly 60 µg/L in late April. Chlorophyll-a declined in May and June but appeared to peak near 140 ug/L in July. Algal blooms occurred, and these influenced run length. Four runs ranged in length from 10 to 22 days when mean chlorophyll-a values were 8 to 138 µg/L. Runs of 34 to 123 days were associated with chlorophyll-a values of 1 to 4 µg/L. Algae removal, as measured by chlorophyll-a reductions, was quite high and similar to removal of other particulate matter (generally approaching 99%).

Raw water quality limits for slow sand filters are stringent because particulate matter tends to be removed at the top of the filter and because slow sand filters have limited capability to remove inorganic contaminants and synthetic organic chemicals. Cleasby et al. (1984 a) reported that enumeration of algae or performing a surrogate measure of algal population was necessary to judge the suitability of raw water for slow sand filtration. Fox et al. (1984) reported that treatment of Ohio River water (0.4-23 NTU) resulted in progressively poorer filtered water quality over 250 days of operation, with effluent turbidity exceeding 1 NTU during the last 20 days of operation, and time to terminal head loss (0.4 m) decreasing from 98 days to 6 days. During the first 230 days, mean influent turbidity ranged from 2.4 to 7.6 NTU, levels that do not seem excessively high. Average raw water turbidity was 10 NTU or lower at 90% of the operating plants surveyed by Slezak and Sims (1984). Experience thus far suggests that the most reliable way to determine treatability of water by slow sand filtration is to conduct an extended pilot plant study.

Slow sand filters are simple to operate and maintain, when raw water quality is appropriate and when the plants are small enough that complicated equipment is not needed for filter scraping. Daily duties at a small installation (10,000 to 1,000,000 L/day) would include reading and recording head loss, flow rates or totals, chlorine residual, raw and filtered water turbidity, and adjusting flow.

Cullen and Letterman (1985) studied filter scraping at seven slow sand filtration plants in New York. Average flows ranged from 1 to 23 million L/day. Scraping, or removal of a thin layer of sand when terminal head loss is reached, required an average of 5 hours per 100 m^2 of filter surface. The thickness of the layer removed was typically 2 to 3 cm. The frequency of scraping would be determined by run length, which would be influenced by the turbidity and algae in the raw water. After a sand filter has been scraped a number of times, the full depth of the bed is restored in an operation called resanding. Cullen and Letterman estimated that resanding a depth of 15 to 30 cm would require 48-59 hours of labor per 100 m^2.

The advantages of slow sand filters are related mainly to the simplicity inherent in the process. Small plants are simply to construct. Simple, manually controlled valves can serve to control flow. Head loss can be measured by a piezometer. Because changes in head loss occur slowly, recording equipment is not needed. Coagulant chemicals are not used in slow sand filtration, so operators do not need to understand coagulation chemistry. Chemical feed pumps would not be needed for coagulant chemicals, so fewer pumps would be used, lowering mechanical maintenance work. Operator skills do not need to be as high as for plants using cogulation. Another advantage associated with absence of coagulation is a minimum of waste disposal problems. Scraped sand is essentially the only waste, and often it is washed and reused.

Many of the disadvantages of slow sand filtration are also related to the absence of coagulation. Without pretreatment, limitations exist on the quality of water that is suitable for slow sand filtration. These were explained earlier. Because modifying a slow sand filter plant to treat a difficult water might be costly, or not possible, pilot studies should be performed to verify treatability. In addition, a study should be conducted to establish that the raw water source is not likely to change or deteriorate in quality to such a degree that the water would become untreatable in the future. This may not always be possible to ascertain, but an effort should be made to predict what sort of human activities or development might happen in the foreseeable future. This would at least alert authorities to possible need for changes in treatment if raw water quality deteriorated. Because pretreatment is minimal or non existant at slow sand filter plants, little capability generally exists to remove synthetic organic chemicals, trihalomethane precursors, and dissolved inorganic substances such as heavy metals. In addition, very fine clays or glacial flour may not be readily removed. Finally, slow sand filters may not be appropriate for medium to large installations in the USA, because of operating labor costs and land costs. The trend for large systems is to automate and use mechanical equipment where possible, but cleaning enclosed slow sand filters by mechanical means is very difficult. Thus, they seem most appropriate for small systems located on very high quality source waters.

DIATOMACEOUS EARTH FILTRATION

Diatomaceous earth (DE) filters have been studied for removal of a variety of contaminants. They have been shown to attain excellent removal of Giardia cysts over a broad range of operating conditions. Cyst removals exceeding 99%, and often 99.9%, were reported by Lange et al. (1986) for filtration rates of 2.4 to 9.6 m/hr, for temperatures from 3.5 to 15°C, and for four different grades of diatomaceous earth (Celite 545®, Celite 535®, Celite 503®, and Hyflo Super-Cel®).*

Pyper (1985) reported 99.97% for one DE filter run in which Giardia cysts were added. Logsdon et al. (1981) reported that when sufficient DE precoat and body feed were used, removal of 9 µm radioactive beads was nearly always 99.9% or higher. Use of a precoat of at least 1.0 kg/m^2 was shown to

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* Mention or use of commercial products does not constitute endorsement by the U.S. Environmental Protection Agency.

be appropriate for obtaining most effective removal of the 9 µm particles. They also reported that eleven filter runs were made with *G. muris* cysts at filtration rates of 2.2 to 3.5 m/hr, with Celite 535® precoat and body feed. Cyst removal exceeded 99.0% in all runs, and exceeded 99.9% in five of the runs. DeWalle *et al*. (1984) reported on four DE filter runs conducted for *Giardia* cyst removal. Cyst removal exceeded 99% in each of the four runs. The overall results of all research for *Giardia* cyst removal indicate that DE filtration is very effective for controlling *Giardia* cysts. Factors important to continued effective performance are using adequate precoat and body feed, and keeping the septum very clean (good cleaning at the end of each run).

Removal of total coliform bacteria by DE filtration was studied extensively at Colorado State University by Lange *et al*. (1986). Coliform removals were strongly influenced by the grade of diatomaceous earth used. Coarser grades attained removals ranging from 30% to 50% for Celite 545® and from 50% to 70% with Celite 503®. The fine grades, with smaller pores, were considerably more effective. Removal with Celite 512® was 92% to 96%, and total coliform removal with Super-Cel® was 99.92% to greater than 99.98%.

Malina *et al*. (1971) reported that a high percentage of removal could be attained for poliovirus when coated DE filter aid was used or when cationic polymer was added to the raw water. In one 12-hour filter run, diatomaceous earth coated with 1 mg of cationic polymer per gram of DE produced filtered water in which no viruses were recovered from 11 samples (removal >99.95%). One of 12 samples was positive, and in this instance, virus removal was 99%. In a 12-hour run in which uncoated DE was used and 0.14 mg/L of cationic polymer was added to the raw water, no viruses were recovered from any of the

12 samples analyzed.

Turbidity removal when treating Horsetooth Reservoir water, as reported by Lange et al. (1986), was less than 20% for the grades of diatomaceous earth commonly used for water treatment (Celite 545®, Celite 535®, Celite 503®, and Hyflo Super-Cel®). Turbidity of the Horsetooth Reservoir raw water ranged from 4.5 to 5.4 NTU. The finest grade tested, Filter-Cel®, could reduce the turbidity by over 95%. In contrast to these results, Logsdon et al. (1981) reported that turbidity reductions of 56% to 78% were attained with Celite 535® when raw water turbidity ranged from 0.95 to 2.5 NTU, but little change was observed when raw water turbidity ranged from 0.24 to 0.45 NTU. Pyper (1985) reported an average turbidity reduction of 71%, with an effluent quality of 0.5 NTU.

Pyper evaluated DE filtration for removal of THM precursor in Vermont. Results showed no difference between the raw water and the filtered water, suggesting that the THM precursor material present in Coburn Pond was dissolved. The water was colored (24 CU, average), and this may explain the lack of change during filtration, because DE filtration alone does not remove color, a known precursor.

Because turbidity removal with the grades of diatomaceous earth commonly used for water treatment was so low when Horsetooth Reservoir water was filtered, the Colorado State University researchers investigated the nature of the turbidity (Bellamy et al., 1984). When 5.6 NTU raw water was filtered, turbidity was reduced 2% by a 5 μm pore size membrane, 36% by a 1.2 μm membrane, 73% by a 0.45 μm membrane, and 91% by a 0.22 μm membrane. Most of the light scattering matter in the water (the cause of the turbidity) was made up of particles that could pass through 1.2 μm pores, and thus fine enough to pass through typical potable water grades of DE.

Additional work was done at Colorado State University to improve the capabilities of DE filtration. In order to alter the surface properties of diatomaceous earth, aluminum hydroxide was precipitated to the surface of a DE slurry. With 0.05 grams of alum per gram of Celite 545®, total coliform removal was 99.86%, as compared to 30% to 50% removal for uncoated Celite 545®. For the same grade of DE, turbidity removal was 98%, for coated DE vs. under 20% for uncoated DE (Lange et al., 1986). These results show that the straining mechanism of removal can be augmented by a surface attachment removal mechanism if DE is given an electropositive coating.

Limits on the quality of raw water that would be appropriate for DE filtration are not easy to set. The process removes particulate matter by trapping it within the filter cake. As the concentration of particulate matter in raw water increases the load applied to the filter cake increases. To maintain high permeability of the filter cake and good head loss characteristics, body feed diatomaceous earth is added to the raw water. A rule of thumb is that higher raw water particle concentrations require more body feed, if the nature of the particles does not change. The nature of the particles being removed is quite important though - especially the compressibility. Rigid turbidity-causing particles, such as very fine sand, would not block or blind the filter cake, but compressible particles, such as algae, coagulation floc, precipitated iron, or biological matter could blind the filter cake. Pilot filtration studies are advisable if the water in question is not already being treated by DE filtration. Such studies would establish the appropriate grade of DE to use to obtain the desired effluent turbidity, the amount of body feed to add under conditions of the test runs, and the approximate length of filter run to expect. Letterman and Logsdon (1976) surveyed 13 DE filtration plants and reported that filtered water turbidities above 1 NTU or filter runs of 6 or fewer hours were observed at DE plants having maximum raw water turbidities of 20 NTU or greater (Fig. 1). This figure shows the percentage of plants exceeding specified values for minimum, average, and maximum raw water turbidity. Symbols shown in the legend identify plant problems with high filtered water turbidity or short runs or both.

Operation and maintenance of diatomaceous earth filters is somewhat more complex than for slow sand filters, but less complicated than coagulation-filtration. Daily monitoring would include turbidity, disinfection residual, rate of water production with adjustments if needed, filter head loss, and rate of use of body feed. Periodic chores would include preparation of body feed slurry and precoat slurry and maintenance checks on body feed and precoat pumps. Also, filters would need to be backwashed periodically, but disposal of spent filter cake should present few problems, because it is not gelatinous and dries readily. Filter elements (septa) need to be kept very clean. The cleanliness of the septa can be readily checked if vacuum filters or quick-opening pressure filters are used. Because of the number of pumps, valves, and other mechanical items in use at a DE filtration plant, operators should possess good mechanical skills. Knowledge of coagulation chemistry would not be needed unless the diatomaceous earth was conditioned by the alum coating technique.

Diatomaceous earth filtration has several important advantages, especially with respect to treating waters that may contain Giardia cysts. The process has been shown in four studies to be very effective for cyst removal, and the removal efficiency is not affected by very low temperatures. Different grades of diatomaceous earth can be kept on hand, giving the operator some flexibility if the grade in use passes too many turbidity causing particles. If necessary, the surface attachment properties of the coarse grades of diatomaceous earth can be markedly enhanced by the alum coating procedure. Diatomaceous earth filter plants do not require large land area, and are in use for capacities up to 50 or 60 million L/day.

Among the disadvantages of diatomaceous earth are the need for high quality raw water, the inability to remove dissolved substances, and the inability to remove very fine particles with plain diatomaceous earth. Excessive suspended solids (turbidity, algae) in raw water can cause short filter runs. Bubbles may form and collapse in the filter cake if the vacuum DE filters are used to treat cold, highly oxygenated water. If pressure DE filters are used and operated to high head loss to obtain long runs and economical use of DE precoat material, high energy costs may result.

COAGULATION-FILTRATION

The process train used most often in the United States for filtration involves chemical pretreatment (coagulation, and frequently flocculation and sedimentation) followed by deep bed granular media filtration. Most U.S. coagulation-filtration research for Giardia cyst removal has focused on the coagulation-filtration (in-line) or coagulation-flocculation-filtration (direct filtration) variations of the process, because waterborne giardiasis outbreaks tended to be observed in regions of the country that had low turbidity waters which were thought to be suitable for such treatment. Research by Logsdon et al. (1981), De Walle et al. (1984), and Al-Ani et al. (1986) involved coagulation with alum, or alum plus a polymer; filtration through sand or dual media at 5 to 14 meters/hr; and temperature ranging from 3° to

20°C. Later research (Logsdon et al., 1985) was conducted on conventional treatment, with alum or alum and polymer, dual media and three monomedia types (sand, anthracite, GAC), filtration at 7 m/hr, and room temperatures (about 25°C).

Results of the three cited direct filtration studies indicate that Giardia cyst removal can exceed 99.0% or even 99.9% when the raw water is coagulated properly and filtered. Results of Logsdon et al. (1981) and De Walle et al. (1984) indicated that with proper pretreatment, cyst removal exceeded 99.0% when filtered water turbidity was below 0.30 NTU. Al-Ani et al. (1986) showed that cyst removal of 99% or more was likely to occur if turbidity removal was 70% or more, when raw waters in the 0.2 to 1 NTU range were treated. This would produce filtered waters in the 0.06 to 0.30 NTU range.

All of the above researchers showed that dependable cyst removal results can not be attained if a clear water (about 1 NTU) is filtered without being properly coagulated. Use of no coagulant, or of an improper dose, resulted in erratic cyst removal results. In addition, DeWalle et al. (1984) showed that for alum coagulation, using the proper pH is necessary when soft, low alkalinity water is treated. They observed effective treatment at pH 5.6 and 6.2, but at pH 6.8 with alum coagulation, cyst removal was reduced from 99% to 95%.

The coagulation-filtration process can remove a variety of contaminants. Robeck et al. (1962) showed that direct filtration could remove 90% to 99% of viruses, while conventional treatment removals consistently were 99%. McCormick and King (1982) stated that coliform removal by direct filtration was practically 100% when filtered water turbidity was 0.10 NTU or less.

Cleasby et al. (1984) reported that in-line filtration removed more than 86% of the total coliform bacteria in raw water, after the first hour of the filter run had passed, in 10 test runs. Edzwald (1986) showed that direct filtration could remove nonpurgeable total organic carbon (NPTOC) and organic precursor materials that form trihalomethanes (TTHMFP, or total trihalomethane formation potential). With cationic polymer as the primary coagulant, both NPTOC removal and TTHMFP removal were about 40% whereas with alum as the primary coagulant removals of NPTOC and TTHMFP were nearly 60%. With the same waters, when conventional treatment was employed with alum as the primary coagulant, removals of NPTOC and THMFP were about 70%. Cleasby et al. (1984 a) reported that waters with low to moderate algal populations, water could be treated by direct filtration. Water with few algae had a chlorophyll-a concentration of less than 5 µg/L (Cleasby et al. 1984 b). Water with an algal population sufficient to result in a chlorophyll-a concentration of 130 µg/L could not be effectively treated by direct filtration without prechlorination.

Suggested limits on raw water quality for sources receiving complete conventional treatment (including predisinfection, coagulation, sedimentation, rapid granular filtration, and post disinfection) were given in the "Manual For Evaluating Public Drinking Water Supplies" as a monthly geometric mean of not more than 2,000 fecal coliform per 100 mL or a monthly geometric mean of not more than 20,000 total coliform bacteria per 100 mL, color not to exceed 75 units, odor not to exceed a threshold odor number of 5, and turbidity not to be so high as to overload the water treatment works (U.S. Environmental Protection Agency, Water Supply Division, 1980).

Suggested limits on raw water quality for direct filtration and in-line filtration are much more stringent. Cleasby et al. (1984 a) suggested that average raw water turbidity should depend on whether the primary coagulant is alum or a cationic polymer, and on whether algal population is low or moderate. Suggested values ranged from 7 NTU for moderate algae and alum coagulation to 16 NTU for low algae and cationic polymer coagulation. The Direct Filtration Subcommittee of the AWWA Filtration Committee (Bishop et al. 1980) reported that waters with less than 40 units of color, turbidity below 5 NTU, iron less than 0.3 mg/L, manganese less than 0.05 mg/L, and algae counts up to 2000 ASU/mL appeared to be "perfect candidates for direct filtration." In a survey of 17 direct filtration plants (Letterman and Logsdon, 1976), short filter runs (6 or fewer hours) were occasionally observed when maximum raw water turbidity was 8 NTU or higher, and both short runs and filtered water turbidity above 1 NTU were sometimes observed when raw water turbidity was 20 NTU or higher (Fig. 2). This figure shows the percentage of plants exceeding specified values for minimum, average, and maximum raw water turbidity. Symbols shown in the legend identify plant problems with high filtered water turbidity or short runs or both. From the work of Edzwald (1986), it can be inferred that if the THM formation potential of a water exceeds 0.20 mg/L, direct filtration may not be able to produce a water that will meet the 0.10 mg/L MCL for trihalomethanes.

Operation and maintenance for coagulation-filtration plants can be more demanding than that for DE plants or slow sand filter plants. Both conventional plants and direct filtration plants should be monitored carefully, because failure to obtain optimum coagulation can result in poor filter performance. Although conventional plants are generally considered to have a "margin of safety" with respect to coagulation control, because of the hours of detention time afforded by settling basins, if coagulation control is lost at the chemical feed and rapid mix point, and if this goes unnoticed until the poorly coagulated water reaches the filters, plant operators could find themselves in the dilemma of having settling basins full of water that could not be filtered successfully.

Coagulation monitoring and control are very important, whether or not the plant employs sedimentation. One traditional approach to control is jar testing. For waters of perhaps 10 NTU or higher, jar testing combined with continuous monitoring of the turbidity of the filtered water at individual filters is an approach frequently used. If raw water quality can change rapidly, or if the raw water turbidity is low (below 10 NTU), jar tests may not be very effective, because of the time required for testing, or because of the smaller differences in raw and settled water turbidities. In such instances, coagulant dose control by zeta potential instrumentation, a streaming current detector, or a pilot filter may be appropriate. Wagner and Hudson (1982) suggested that filter paper filtration using Whatman No. 40 paper could give information on the treatment levels that produce acceptable water quality. Other appropriate monitoring would include pH, head loss, chemical feed, and raw and filtered water turbidity.

Maintenance operations would include care of chemical mixers and feeders, perhaps flocculation basin mixers and sludge removal equipment in settling basins. Filter backwashing is necessary, and backwash water and settling basin sludge may require treatment and ultimate disposal. If sludge removal from settling basins is not done mechanically, periodic manual basin cleaning would be needed.

The level of operating skill needed at coagulation-filtration plants is substantial. In order to effectively and efficiently control the coagulation-filtration process and attain low filtered water turbidity, operators need to understand the chemical aspects of coagulation. Large and medium sized plants are able to hire and keep trained operators who can effectively operate coagulation-filtration plants. On the other hand, small plants may not have the resources to hire or train operators who have a solid understanding of coagulation. This can lead to problems of poor treated water quality, if operators are unable to adjust treatment when raw water quality changes.

Of the three processes discussed in this paper, coagulation-filtration has the greatest flexiblity in the kind and concentration of contaminants that can be removed in the process, especially when sedimentation is employed. Conventional treatment can handle the widest range in raw water quality, and has been in use for several decades. Coagulation-filtration plants, because they employ more treatment processes, can be designed with the most flexibility in terms of the number of processes used. For example, settling might be used for muddy water but bypassed when raw water turbidity is low. Recent developments, such as use of media in the 1 to 2 mm size range, beds about 2 meters in depth, and filtration rates of 25 m/hr or higher provide even more treatment capability for the coagulation-filtration process, but until experience with such plants is gained, the very high rates of filtration probably should be considered only at large water utilities with well-trained, full time operators and laboratory personnel.

In spite of the many advantages that can be listed for coagulation-filtration, a number of drawbacks exist. The most important potential problem is this: for rapid rate granular media filtration to be an effective process for removal of particulate matter, the chemistry of the water must be manipulated so that coagulation is effective. This can be done through adjustment of pH and addition of an inorganic coagulant or polymer or both. At utilities that serve 50,000 to 100,000 persons or more, hiring one or more scientists to work in a water quality control laboratory can be considered feasible, as it is presently being done. At water utilities too small to employ a chemist, operation of the coagulant-filtration process may be less than optimum. Testing by persons who understand the process can establish the proper chemical treatment under the raw water quality conditions existing during the test period. The ability of operators to understand the implications of changing raw water qualty and make proper adjustments could result in lower process efficiency, though. A fundamental concept is that coagulation chemistry is not influenced by the magnitude of the flow in a plant. Factors such as pH, alkalinity, and temperature must be considered, regardless of the size of the plant.

A particular concern in northern latitudes or mountainous areas where giardiasis outbreaks may have occurred is the difficulty of effectively coagulating and filtering cold, clear waters. When the raw water turbidity is close to 1 NTU, some plant operators may question the value of adding a coagulant. Others may be discouraged by the apparent difficulty in treating a clear water at temperatures close to 0°C, and in both instances, operators may shut off the chemical feeders. Coagulant feed should never be interrupted nor shut off. Techniques are available for treating cold waters and low turbidity waters. Performing jar tests with the jars in an ice water bath is appropriate. Use of paper filters or small (2.5 cm) mini-filters with beds 30 cm deep, or shallower, could be used to evaluate filterability of clear waters. Use of streaming current detectors as an on-line coagulant dose control device appears to work well in winter. Experience indicates that coagulation-filtration plants can produce high quality water even when temperature and turbidity in the raw water are low. The Duluth, Minnesota filtration plant consistently produced filtered water below 0.10 NTU and attained 99% to 99.99% reductions of asbestos fibers even when temperatures were in the 3° to 5°C range and raw water turbidity was 1 NTU (Logsdon et al., 1983).

CONCLUSIONS

1. Each of the three filtration processes reviewed is different, and no single process is ideal in every circumstance.
2. As process complexity increases, from slow sand filtration, to DE filtration, to coagulation-filtration, the skill level needed for effective operation increases.
3. As process complexity increases, producing high quality filtered water increasingly becomes dependent on operator skill and ability.
4. A variety of filtration processes have been used successfully either on a pilot plant scale or at full scale to remove *Giardia* cysts from water.
5. Slow sand filtration, DE filtration, and the coagulation-filtration (in-line or direct filtration) processes used without sedimentation are all affected by raw water quality, with respect to both filtered water quality and plant performance characteristics, such as filter run length. Therefore, if use of any of these processes is contemplated with a water source that is not presently being treated successfully by the process, performing a pilot plant study before design and construction of the treatment plant is highly advisable.

6. Even though important limitations exist and must be taken into account, filtration technology capable of removing 99% or more of the Giardia cysts from drinking water exists and is in use in many locations.

REFERENCES

Al-Ani, M.Y., D. W. Hendricks, G. S. Logsdon, and C. P. Hibler. 1986. Removing Giardia Cysts from Low Turbidity Waters by Rapid Rate Filtration. Jour. American Water Works Assoc. 78:5:66-73.

Bellamy, W. D., K. P. Lange, and D. W. Hendricks. 1984. Filtration of Giardia Cysts and Other Substances: Volume 1. Diatomaceous Earth Filtration. EPA-600/2-84-114, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1967.

Bellamy, W. D., D. W. Hendricks, and G. S. Logsdon. 1985 a. Slow Sand Filtration: Influences of Selected Process Variables. Jour. American Water Works Assoc. 77:12:62-66.

Bellamy, W. D., G. P. Silverman, and D. W. Hendricks. 1985 b. Filtration of Giardia Cysts and Other Substances: Volume 2. Slow Sand Filtration. EPA 600/2-85/026, U.S. Environmental Protection Agency, Cincinnati, Ohio.

Bishop, S., T. F. Craft, D. R. Fisher, M. Ghosh, P.W. Prendiville, K. J. Roberts, S. Steimle, and J. Thompson. 1980. The Status of Direct Filtration, Committee Report. Jour. American Water Works Assoc. 72:7: 405-411.

Cleasby, J. L., D. J. Hilmoe, and C. J. Dimitracopoulos. 1984 a. Slow Sand and Direct In-line Filtration of a Surface Water. Jour. American Water Works Assoc. 76:12:44-55.

Cleasby, J. L., D. J. Hilmoe, C. Dimitracopoulos, and L. M. Diaz-Bossio. 1984 b. Effective Filtration of Small Water Supplies. EPA-600/2-84-083, U.S. Environmental Protection Agency, Cincinnati, Ohio.

Craun, G. F. 1986. Waterborne Giardiasis in the United States 1965-1984. Lancet II: 8505:513-514.

DeWalle, F. B., J. Engeset, and W. Lawrence. 1984. Removal of Giardia lamblia Cysts by Drinking Water Treatment Plants. EPA-600/2-84-069, U.S. Environmental Protection Agency, Cincinnati, Ohio.

Edzwald, J. K. 1986. Conventional Water Treatment and Direct Filtration: Treatment and Removal of Total Organic Carbon and Trihalomethane Precursors, p. 199-236. In N. M. Ram, E. J. Calabrese, and R. F. Christman (eds.) Organic Carcinogens in Drinking Water: Detection, Treatment and Risk Assessment, John Wiley & Sons, N.Y.

Fox, K. R., R. J. Miltner, G. S. Logsdon, D. L. Dicks, and L. F. Drolet. 1984. Pilot Plant Studies of Slow-Rate Filtration. Jour. American Water Works Assoc. 76:2:62-68.

Lange, K. P., W. D. Bellamy, D. W. Hendricks, and G. S. Logsdon. 1986. Diatomaceous Earth Filtration of Giardia Cysts and Other Substances. Jour. American Water Works Assoc. 78:1:76-84.

Letterman, R. D., and G. S. Logsdon. 1976. Survey of Direct Filtration Practice - Preliminary Report. Presented at American Water Works Association Annual Conference, New Orleans, Louisiana. June, 1976.

Letterman, R. D., and T. R. Cullen, Jr. 1985. Slow Sand Filter Maintenance: Costs and Effects on Water Quality. EPA/600/2-85/056, U.S Environmental Protection Agency, Cincinnati, Ohio.

Logsdon, G. S., J. M. Symons, R. L. Hoye, Jr., and M. M. Arozarena. 1981. Alternative Filtration Methods for Removal of *Giardia* Cysts and Cyst Models. Jour. American Water Works Assoc. *73*:2:111-118.

Logsdon, G. S., G. L. Evavold, J. L. Patton, and J. Watkins, Jr. 1983. Filter Plant Design for Asbestos Fiber Removal. Jour. of Enviornmental Engineering. *109*:4:900-914.

Logsdon, G. S., V. C. Thurman, E. S. Frindt, and J. G. Stoecker. 1985. Evaluating Sedimentation and Various Filter Media for Removal of *Giardia* Cysts. Jour. American Water Works Assoc. *77*:2:61-66.

Malina, J. F., Jr., B. D. Moore, and J. L. Marshall. 1972. Poliovirus Removal by Diatomaceous Earth Filtration. Center for Research in Water Resources, The University of Texas, Austin, Texas.

McCormick, R. F. and P. H. King. 1982. Factors That Affect Use of Direct Filtration in Treating Surface Waters. Jour. American Water Works Assoc. *74*:5:234-242.

Pavoni, J. L., M. W. Tenney, and W. F. Echelberger, Jr. 1972. Bacterial Exocellular Polymers and Biological Flocculation. Jour. Water Pollution Control Federation *44*:3:414-431.

Pyper, G. R. 1985. Slow Sand Filter and Package Treatment Plant Evaluation: Operating Costs and Removal of Bacteria, *Giardia*, and Trihalomethanes. EPA/600/2-85/052, U.S. Environmental Protection Agency, Cincinnati, Ohio.

Robeck, G. G., N. A. Clarke, and K. A. Dostal. 1962. Effectiveness of Water Treatment Processes in Virus Removal. Jour. American Water Works Assoc. *54*:10:1275-1290.

Slezak, L. A., and R. C. Sims. 1984. The Application and Effectiveness of Slow Sand Filtration in the United States. Jour. American Water Works Assoc. 76:12:38-43.

Taylor, E. W. No Date. Forty-Fifth Report on the Results of the Bacteriological, Chemical and Biological Examination of the London Waters for the Years 1971-1973. Metropolitan Water Board, London, England.

Wagner, E. G., and H. E. Hudson, Jr. 1982. Low-Dosage High-Rate Direct Filtration. Jour. American Water Works Assoc. 74:5:256-261.

Water Supply Division, U.S. Environmental Protection Agency. 1980. Manual for Evaluating Public Drinking Water Supplies. EPA-430/9-75-011. Washington, D.C.

TABLE 1. PARAMETERS IN SLOW SAND FILTER RESEARCH

Filter Design				Raw Water Quality				Reference
Sand Size, mm	Uniformity Coefficient	Filtration Rate, m/hr	Bed Depth, m	Temp., °C	Turbidity, NTU	Total[1] Coliform per 100 mL	Other	
0.17	2.1	0.12	0.76	about 25° (room temp.)	<1 to 10	10 to 10,000		Fox et al. 1984
0.32	1.4	0.12	0.94	2° to 28°	<1 to >30	40 to 10,000	0.2 to 143 mg/m^3 chlorophyll-a	Cleasby et al. 1984 b
0.33	2.8	0.08	1.07	0° to 25°	0.2 to 59	1 to 8,700	(2.1 to 26)x10^6 *Giardia* cyst spiked [35 to 425 cyst/L if diluted over filter uniformly]	Pyper 1985
0.13 to 0.62	1.5 to 1.6	0.04 to 0.40	0.48 to 0.97	2° to 17°	2.7 to 11	0 to 209,000	50 to 5,075 *Giardia* cysts/L spiked	Bellamy et al. 1985a, 1985b

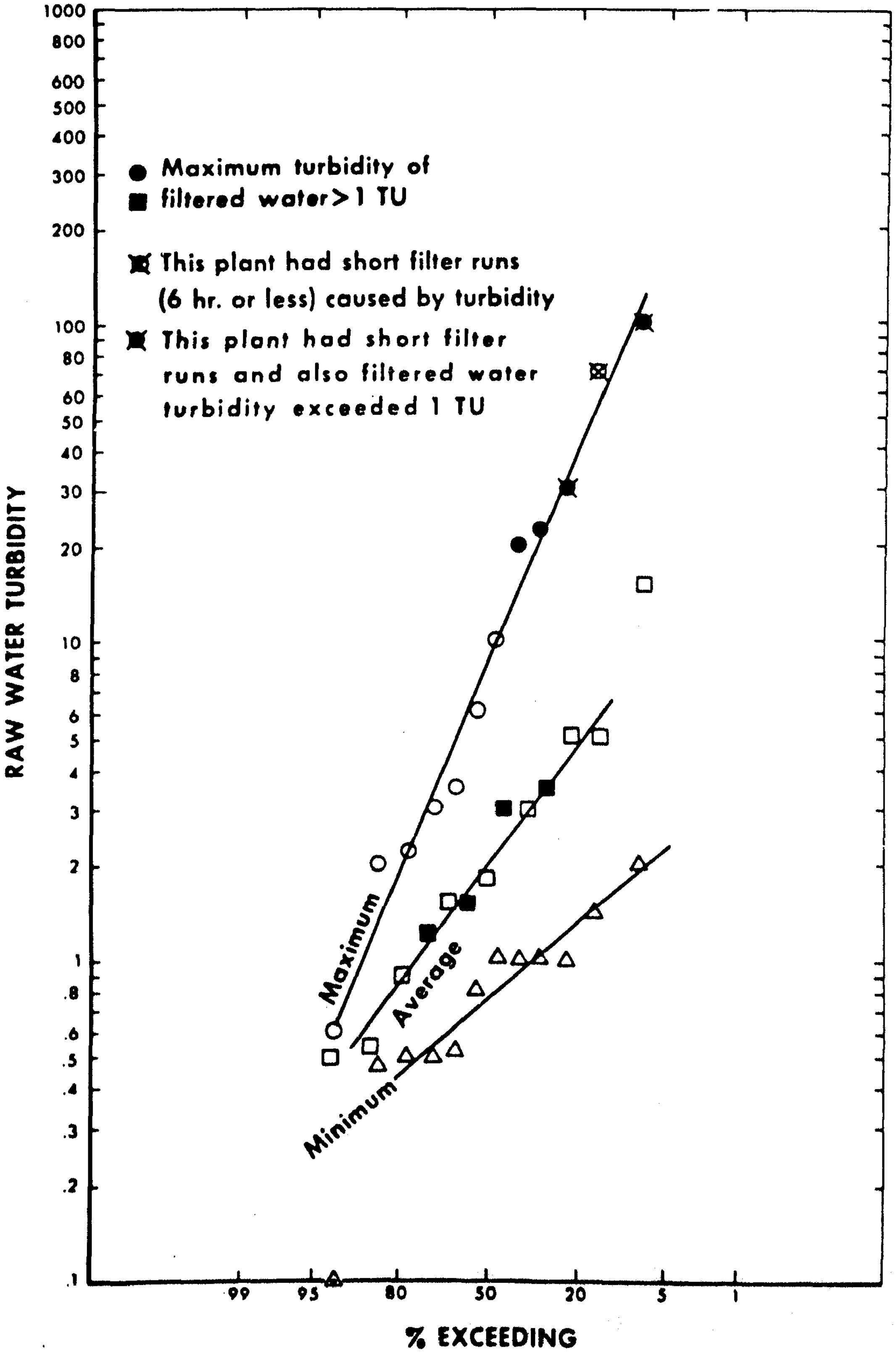

FIGURE 1 **Influence of raw water turbidity on diatomaceous earth plant performance**

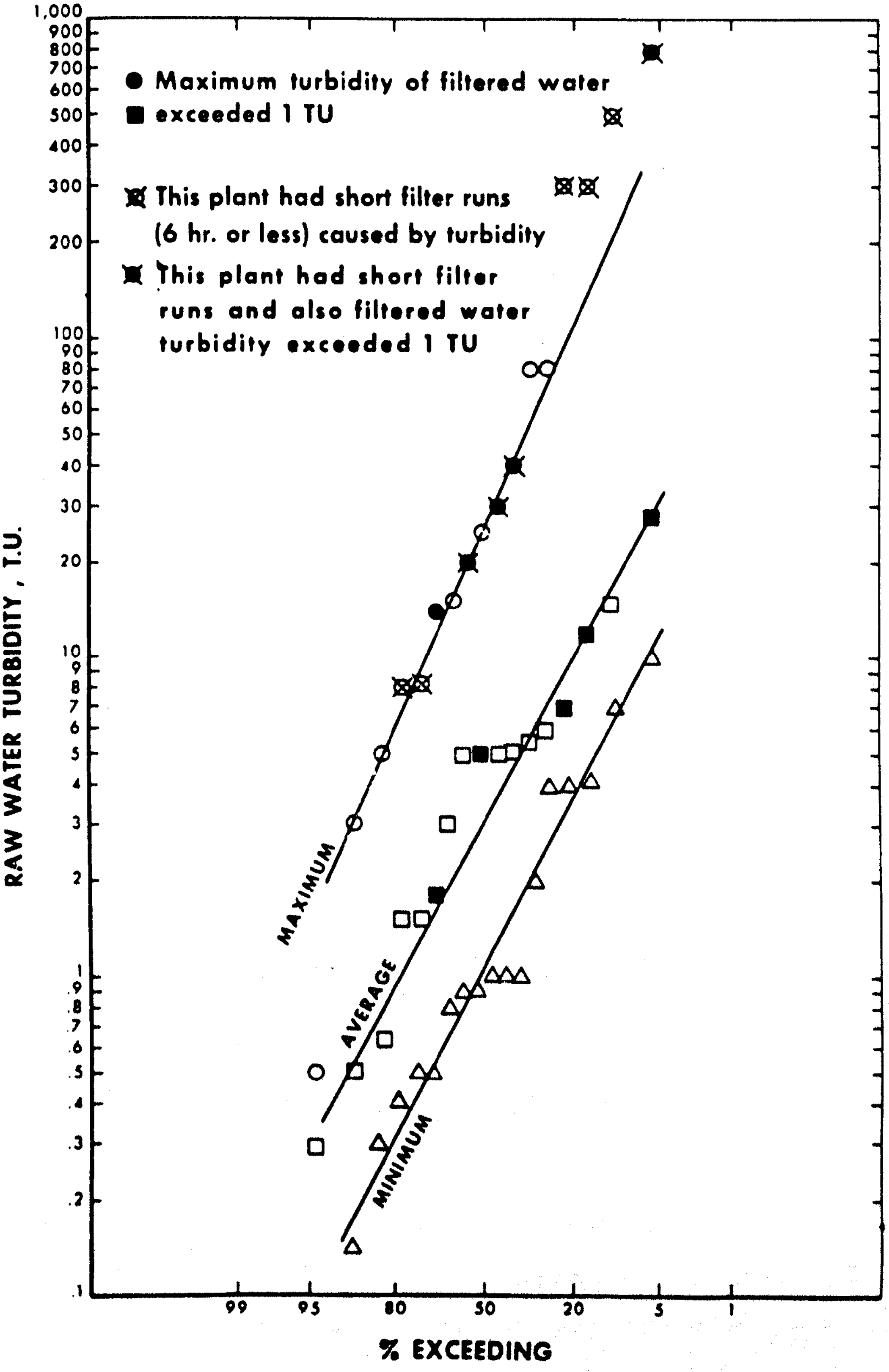

FIGURE 2 Influence of raw water turbidity on granular media plant performance