TREATMENT PLANT EVALUATION FOR PARTICULATE CONTAMINANT REMOVAL

Gary S. Logsdon, Chief
Microbiological Treatment Branch
Drinking Water Research Division
Water Engineering Research Laboratory
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

Water treatment plants may be evaluated for a variety of reasons. These include assessments of competence of operating staff, of physical condition of facilities, of hydraulics of treatment processes, and of quality of the treated water. Facility evaluations should be carefully planned before they are started. Just as manuscript writing generally is aided by first preparing an outline, plant evaluation is improved by first planning the evaluation. As it proceeds the plant evaluation should be carried out in an organized, logical fashion that results in consideration of all necessary and important aspects of the plant and its operation.

This paper is intended to serve as an aid for those who may conduct evaluations for the purposes of improving upon the removal of particulate matter and lowering the effluent turbidity from filtration plants where chemical coagulation is practiced as a part of the treatment process. Producing water with lower turbidity may be a treatment goal for a number of reasons. Compliance with water quality regulations is one. Another would be removal particulate contaminants such as Giardia cysts or asbestos fibers. Yet another would be improved treatment for removal of organic materials, so that the disinfectant dose could be lowered, in order to maintain effective disinfection but minimize formation of disinfection byproducts or offensive tastes and odors.

PROJECT GOALS

Before a filtration plant is evaluated, the parties involved should get together and define the goals for the project. What is to be accomplished should be thoughtfully set forth. Is the purpose improvement in water quality? Is greater production of water a goal? Is a reduction of operating costs, such as for treatment chemicals, desired? When the options are considered, and goals for the study are agreed upon, then the detailed planning for the study can be done. Preparing a written statement of the goals would be helpful.

INFORMATION, PAST AND PRESENT

The water utility's offices and laboratory may contain much valuable information that would aid the engineer in making a plant evaluation. Facility blueprints and diagrams can be used for preliminary hydraulic evaluations. Plant records of water quality should be obtained. Chemi-

---

Presented at Preconference Seminar, Pacific Northwest Section, American Water Works Association, Bellevue, Washington, May 1987 and Water Quality Seminar, Virginia Section, American Water Works Association, Roanoke, Virginia, April 1987 cal, microbiological and physical quality of treated water should be reviewed and compared with corresponding data for raw water. How much improvement in water quality is attained by treatment? How often does raw water vary and what are the influences of raw water quality changes on treated water quality? Seasonal effects may be important and should be kept in mind as data are reviewed. Factors such as low temperatures in winter, spring runoff, summer and fall algal blooms, and low flow conditions may influence finished water quality. The unique aspects of each water source should be kept in mind as plant evaluations are made.

Interpretation of large amounts of data can sometimes be aided by use of probability plots. As an example, Figure 1 by Baumann[1] shows the percentage of time turbidity of Lake Superior raw water at Duluth was equal to or less than a specified value. Turbidity there was less than 20 NTU 99.9% of the time, and was less than 6 NTU 99% of the time, from 1952 to 1972. This type of analysis would not be appropriate if significant changes in water quality had occurred between 1952 and 1972, so that for one portion of time water quality was considerably better or worse than for the other portion of time.

If an increase in water production is planned, present vs. future needs should be carefully considered. Both economic growth and water demand fluctuate up and down. In contrast to some rapidly growing communities others lose industry and population for periods of time. Estimates of future demand need to be developed in a way that involves a broad spectrum of informed people, yet someone needs to be a skeptic, questioning the optimism of community boosters. Realism should govern as plant expansion dreams are started on the path to reality. If additional water is really necessary, the feasibility of higher production rates to attain the desired quantity in lieu of plant expansion can be evaluated. If higher rates are anticipated, the effects of higher rates on water quality must be considered. In some instances, prudent changes in the plant and improvements in operation may result in greater production of better quality water without actual expansion.

After existing records are reviewed, gathering more data may be necessary. When water quality is a concern, raw water is a good place to start. A sanitary survey ought to be performed to identify sources of contamination. If obvious sources are located and if they can be cleaned up, the improvement in raw water quality may be reflected in the finished water. Wastewater treatment and elimination of contamination to raw water are important barriers in the multiple barrier concept, and they should not be overlooked. Better management of logging to control soil erosion and better operation of upstream wastewater treatment plants are examples of practices that could improve raw water quality and yield benefits at a water filtration plant.

Reviewing and developing data related to the water utility will consume extra time at the beginning of a treatment plant evaluation, but the time invested in this effort can be expected to yield a more productive and insightful evaluation.

PLANT HYDRAULICS AND FLOW PATTERNS

Both the quantity and the quality of filtered water can be affected by plant hydraulics. Maximum hydraulic capacity is an obvious limitation. The adverse influences of rate of flow and flow patterns on water quality may not be so obvious, but they can be very important. Flow rate influences detention time, and as flow rate is increased, detention time decreases. Under some circumstances, shorter time for flocculation or sedimentation might lead to poorer water quality. Increased flow rates that result in higher filtration rates may have this effect too, especially if floc is weak.

Flow metering and measurement are very important. Evaluating and controlling plant performance are difficult if flows are unknown. In order for a plant to be operated properly the total flow rate has to be known, on an instantaneous basis or by calculations based on volumetric measurement. Is such equipment in place and working? In addition, whenever flow is divided in a plant, some means should be available for operators to understand how the flow is being split.

Flocculators, settling basins, or filters operated in parallel should have provision for determining flow. Unequal division of flow to two identical settling basins could result in overloading one basin, with poor settled water as a result.

Pressure filters operated in parallel can be operated in a variable, declining rate mode, with the most clogged filter operating at the slowest filtration rate; however, flow meters should be provided at each so operators can determine the actual rate of filtration for each filter. Again, if one or more filters is clogged and not carrying a fair share of the load, other filters may be overloaded and operate at excessively high rates, possibly leading to turbidity breakthrough.

Even if improper division of flow among basins or filters is not a problem, poor distribution of flow within a basin might be. Flocculation basins should be operated in a plug flow mode if it is desired to impart similar mixing energy and time (GT) to all of the water. A single unbaffled flocculation basin resembles a continuously stirred reactor. A properly baffled flocculation basin can have flow characteristics that approach plug flow. Hudson[2] (p. 77) calculated that in a single compartment, continuously stirred basin, 39 percent of the water would pass through the basin in a time shorter than 50 percent of the nominal residence time. In a series of five baffled, continuously stirred basins, only 11 percent of the water would pass through the basin in a time shorter than 50 percent of the nominal residence time.

Because of the importance of hydraulic patterns, short circuiting, and detention times, under some circumstances it will be appropriate to evaluate flow by performing a tracer study. Lippy (pp. 218-220) has recommended this and given suggested procedures.[3] Although dyes are very sensitive tracers, their use in operating drinking water facilities may be inadvisable. Other tracers are available, including lithium, chlorine, and fluoride. According to Standard Methods[4] the optimum concentration range for measurement of lithium by direct aspiration atomic absorption is 0.1 to 2 mg/L, and the detection limit is 0.002 mg/L. Some caution should be applied if use of fluoride as a tracer upstream of the filter is planned. Standard Methods indicates that polyvalent aluminum can complex with fluoride, the extent depending on pH and the relative levels of fluoride and complexing species. In an extensive study of water filtration at Duluth, Schleppenbach[5] described pilot plant studies that indicated adding fluoride to water before filtration resulted in use of an additional 2 to 4 mg/L of alum in order to obtain the same level of filtered water turbidity that could be attained when no fluoride was added. Chlorine can also be used as a tracer, but chlorine demand and effects of sunlight could influence results. If chlorine demand is satisfied, sunlight is not a factor in closed basins and during hours of darkness.

An excellent guide to evaluation of flow characteristics and residence times is found in "Residence Times in Pretreatment", Chapter 5 in Hudson's book, Water Clarification Processes: Practical Design and Evaluation.[2] Hudson recommended use of step doses, i.e. a sudden increase of tracer fed on a continuous basis, rather than use of a slug dose. The tracer concentration range that must be measured when a step dose is used is much smaller, and this should make tracer analysis easier than if a slug dose is used.

Hudson[2] (p. 75) stated that one of the two categores of deficiences causing water treatment plants to fail to perform as well as expected was hydraulics, including flow distribution, hydraulic inadequacies, incorrect baffling, and lack of consideration of mixing intensity criteria. Because of this great importance, plant hydraulics should not be overlooked.

CHEMICAL FEED SELECTION AND CONTROL

Deep bed, granular media filters that are operated at rates of 2 gallons per minute per square foot, or greater, will not work dependably and efficiently if the raw water is not coagulated properly before it is applied to the filters.[6] In many cases, flocculation and sedimentation are also necessary. This has to be understood clearly by the engineer who evalutes the plant and by the operators who are responsible for controlling coagulation and filtration. Shutting off coagulant chemicals when raw water turbidity is lower than the 1 Nephelometric Turbidity Unit (NTU) Maximum Contaminant Level is never a correct operating procedure.

If adding coagulant chemicals is essential, so is maintaining the proper chemical control of coagulation. The efficacy of inorganic coagulants, especially alum, depends on the pH of the water. Chemical dose is important, both for inorganic coagulants and for polymers. Inadequate doses result in inadequate particle destabilization and coagulation. Overdoses of cationic polymers can result in restabilization of particles. Application of the correct dose of coagulant, on the other hand, results in destabilization of particles, leading to effective flocculation, sedimentation, and filtration. For a more detailed explanation, Edzwald's[7] Chapter 6, "Coagulation", in "Coagulation and Filtration: Back to the Basics" is recommended.

Close attention should be given to the procedure used to select coagulant dose and pH at a filtration plant. Some utilities base coagulation chemistry on past practice. This may be helpful if careful records are kept and charts are prepared so that changes in water chemistry can be accounted for. Even so, actual testing for dose selection should be done by jar testing or other methods. The initial advice on coagulation given at the time the plant was started shouldn't be assumed to be valid to perpetuity.

Probably the most common approach to coagulant chemistry evaluation is jar testing. For turbid waters, jar test results can be based on the turbidity of the settled water. For low turbidity waters, perhaps 5 NTU or lower, changes in raw water turbidity may not be sufficient to clearly indicate optimum chemical doses. Also, at direct filtration plants, sedimentation is not practiced, so evaluating settled water turbidity would be inappropriate for dose selection. Wagner and Hudson[8] suggested that jar test water could be filtered through Whatman No. 40 paper after coagulation and flocculation, and reported similar results for filtered water turbidity using this procedure, pilot filters, and full scale filters. Neuman[9] emphasized the importance of performing jar tests with test water at the same temperature as water in the plant. This is important when cold water is treated, because proper pH and doses may be different for warm vs. cold water. Griffith and Williams[10] evaluated jar testing at Phoenix, Arizona, and reported that the mode of addition of coagulant chemical influenced jar test results. Moffett[11] reported higher doses of alum were needed to destabilize colloidal suspensions when coagulant was added on top of the water vs. at the impeller in a jar test. If chemical is added by mixing into the water, rather than by pouring it on top of the water in the full scale plant, this practice should be mimicked in jar testing. This could be done by using funnels, with the dose of coagulant chemical followed by a rinse of test water in quantity sufficient to displace all coagulant from the stem of the funnel. If rapid mix times are being evaluated, or if mix time is short, chemical should be added to all jars simultaneously. During a plant evaluation, it would be a good idea to watch the plant staff perform a jar test. Also inquire about the frequency of jar testing and the basis for deciding when to test, i.e. seasonal changes, changes in river flow, changes in turbidity, etc. Hudson and Wagner[12] published an excellent paper on performing jar tests and interpreting the results.

Another approach to dose control is based on measurement of electrophoretic mobility. The electrical charge on colloids, depending on its magnitude, can cause the particles to repel each other and remain in suspension, or if it is small enough (near zero), particle collisions can occur and particles will stick together and grow into flocs that settle out, or stick on the filter media.

Electrophoretic mobility can be determined by instruments that measure zeta potential or streaming current potential. Zeta potential measurements are based on the velocity of individual colloids or groups of colloids. Zeta potential is usually determined on grab samples. Streaming current potential is based on the average of the electrophoretic mobility of all of the particles in the water sample. Streaming current detectors analyze discrete samples, but can be set up to do so repeatedly, thus approximating continuous, on-line analysis. The use of streaming current detectors to control coagulant dose is presently (1987) being evaluated by the University of Delaware under sponsorship of the American Water Works Association Research Foundation.[13] When electrophoretic mobility techniques are used to adjust coagulant doses, the validity of such approaches should be verified from time to time by performing a series of jar tests or pilot filter studies with doses at, above, and below the recommended concentration.

Some water utilities use pilot filters to determine appropriate coagulant doses. Proprietary equipment used to filter coagulated water after the rapid mixing step was described by Conley and Evers.[14] Turbidity is monitored continuously, and water is filtered at a high rate. When the turbidity of the water produced by the pilot filter is unsatisfactory, a change in coagulation chemistry is needed. Research on a pilot filter concept for dose selection was conducted by Kreissl et al[15] about two decades ago. They operated clean pilot filters at high rates, to simulate conditions that would be encountered when a clogged filter was operated at a normal rate. They were able to determine coagulant dose with the pilot filters, as a jar test would, but in addition they were able to obtain information on floc strength and the ability to resist turbidity breakthrough at the end of a filter run. They reported that the pilot filter systems they tested could be used to select optimum chemical dosage at filtration plants that did not employ flocculation and sedimentation.

Tests employing pilot filters rather than electrophoretic mobility measurements, or jar tests, would be appropriate for determining floc strength and proper dose of nonionic polymers. Visible changes in floc formation sometimes can be seen in jar tests, but no data on floc stength or head loss in filters can be obtained this way. Nonionic polymers can be used to bridge smaller flocs together and form a large floc that settles better, or to produce a tougher floc that resists turbidity breakthrough during rate changes. Better control of turbidity and Giardia cyst removal, even during filtration rate increases, was attained by Logsdon et al[16] in direct filtration research, when alum and 0.1 mg/L of nonionic polymer were used to condition the water. In a later study Logsdon et al[17] reported that a slightly nonionic high molecular weight polymer could strengthen alum floc and assist retention of the floc and cysts in an 0.9 mm effective size anthracite filter. In this case, polymer-conditioned alum floc filtered in 0.9 mm media produced an effluent turbidity (0.10-0.16 NTU) similar to turbidity produced by 0.42 mm sand filtering alum floc (0.08-0.16 NTU) in an earlier experiment. In both cases, filters were ripened and not exhibiting turbidity breakthrough. Use of polymer can sometimes permit production of high quality water in spite of less than optimum facilities or operation.

After appropriate doses of chemicals are selected for coagulation, it logically follows that the capability to feed the chemicals must exist. Techniques for adding chemicals to raw water vary greatly, from those that give poor results to those that provide efficient and effective utilization of chemicals. Several aspects of chemical feed have to be considered, including flexibility in locations and order for adding chemicals, the actual means of adding and dispersing chemicals, techniques for measuring chemical feed and thus verifying the doses, and kinds of chemicals that are fed.

Flexibility should include the capability to add certain chemicals at more than one point in the treatment train. Points of addition may include near the beginning of a raw water transmission main, just before a rapid mixer, in a rapid mix tank, just before flocculation, before filtration, after filtration as water flows to a clearwell and into backwash water. A sufficient number of feed points should be available so that each chemical has the opportunity to mix completely with the water and function as intended rather than react in a concentrated form with some other chemical being added to the water. Hudson[2] suggested the use of plastic water meters or plastic volumetric cylinders to measure actual feed rates on a short term basis.

The actual mode of chemical addition is extremely important. Inorganic coagulants and polymers should be diluted sufficiently that they readily dissolve and disperse in the raw water, but they shouldn't be diluted so excessively that they become less effective. This aspect of alum feed practice was discussed by Griffith and Williams,[10] who reported that dilution of liquid alum to a 1.5 percent solution gave them satisfactory results. They reported that another investigator found that alum diluted to 0.3% was less effective. For appropriate polymer dilution, manufacturers' recommendations should be followed.

Chemical pumping equipment and piping should be checked. A commonly used feed pump is the diaphragm pump. This device pumps in pulses, like a human heart. If such a pump is used to add coagulant to raw water flowing in a pipe, and is operating at 60 cycles per minute, with pumping occurring only 0.5 second of each 1.0 second cycle, then half of the water comes in intimate contact with alum solution, but half does not. If water in the pipe was flowing at 6 feet per second, each second one 3 foot segment would have no alum, but the other segment would have twice the desired dose. Hudson and Wolfner[18] stated that alum hydrolyzes in a fraction of a second. Thus, some chemical reactions would have taken place before the overdosed and underdosed water could mix. The pulsed flow pattern from a diaphragm pump can be converted to continuous flow by installation of a vertical air-filled pipe or pneumatic tank (an accumulator) downstream from the pump. Such a device should be used in conjunction with a diaphragm pump to obtain maximum efficiency with coagulant chemicals.

Because of the rapidity with which coagulation occurs, the stream of coagulant chemical must be dispersed throughout the entire quantity of raw water in a nearly instantaneous fashion. Chemicals added in a rapid mix chamber should be delivered close to the impeller. Chemicals fed into a pipe should be fed upstream against the flow. Multiple injection points across the area of flow as suggested by Forbes et al[19] are preferred to a single injection point. Another possibility for chemical feed in pipes involves use of orifice plates to create turbulence. Commercially fabricated motionless mixers (static mixers) are available for in-line rapid mixing. The least preferred way of adding coagulant chemicals would be to simply dribble or drop a stream of coagulant onto the surface of the raw water. This is sometimes done in older water plants that employ a rising well for rapid mixing. One such facility was observed by the author at a utility that added not only alum, but also powdered activated carbon to raw water. The PAC suspension dropped onto the water surface at a corner of the rising well and failed to thoroughly blend by the time the water discharged to a flume for distribution to flocculation basins. Samples grabbed from the surface of the flume by means of a glass beaker showed that the water on the side closer to the first flocculation basin had hardly any visible carbon, whereas the water on the side away from the entrance ports to the flocculation basin was dark grey. Different settling basins obviously were receiving different PAC doses. A simple demonstration such as this may suffice to convince a plant operator of the need for improved mixing.

The plant evaluator should note the variety of chemicals being fed. They might include inorganic coagulants, polymers, acid, lime, caustic soda, soda ash, corrosion inhibitors, powdered activated carbon, disinfectant, ammonia, and fluoride. The order of chemical addition can be important. For guidance on this, reference works should be checked, or jar tests should be performed. Certain chemicals interfere with others. For example, powdered activated carbon added for taste and odor control may decrease the chlorine residual, polyphosphate added to sequester iron may reduce the efficacy of zinc as a corrosion inhibitor for asbestos cement pipe,[20] and fluoride added before filtration may complex with aluminum and necessitate use of more alum to coagulate water.[5] The sequence of chemical addition may be based on past practice, or may have been developed over the years on an ad hoc basis. Conducting jar tests to verify that actual practice gives the best results may be advisable.

RAPID MIXING

Moffett[11] called rapid mixing the most important step in the water treatment process. Letterman et al[21] evaluated rapid mixing and showed that a short period of high intensity mixing was the method of choice. Vrale and Jorden[22] evaluated rapid mixer configurations. For alum coagulation, they concluded that in-line mixers (plug flow reactors) were superior, and that a backmix reactor was ineffective. Backmixing systems were better for precipitative lime softening, because the distribution of residence times of particles in the mixer would provide some crystallized $CaCO_3$ that could promote more rapid precipitation.

Another commonly used approach to rapid mixing is addition of chemicals at a hydraulic jump. If this approach is used, chemical should be distributed across the width of the flow stream if possible, because of the rapidity with which coagulation reactions occur.

Although many plants may have only one rapid mixer, some have more than one. If sequential additions of chemicals gives superior jar test or pilot plant results, adding more mixing capability may be advisable. Options would include in-line mixing in a raw water line before the rapid mix compartment, and perhaps subdividing the original rapid mix compartment, if piping permits. Earlier practice typically provided more residence time for rapid mix than is designed for at present, so subdividing may be feasible. The amount of rapid mixing energy applied may influence the quality of water produced, but it is not likely that mixing energy would be varied on a frequent basis by operating personnel. In a plant evaluation, the engineer should consider whether or not large scale changes in mixing energy should be made, rather than try to fine tune mixing energy by a factor of 5 or 10 percent.

FLOCCULATION

At filtration plants that employ coagulation, flocculation is the first optional process. In-line direct filtration plants do not employ flocculation. Other direct filtration plants use flocculation but omit sedimentation. Conventional filtration plants use rapid mixing, flocculation, sedimentation, and filtration. At a direct filtration plant, flocculation could be operated to produce a small, dense floc that would store well in the filter, whereas at a conventional plant a floc that settles well is desired. Differences in purpose should be considered in a plant evaluation.

Because of the need to have some uniformity in flocculation time, flocculation basins should be well baffled so that plug flow can be approximated. Research by Argaman and Kaufman[23] indicated that for equivalent removal of particulate matter, a four-compartment flocculator required less flocculation time and energy (GT) than a single basin flocculator. They stated, "Systems with equal overall residence times will perform better as the degree of compartmentalization increases." Their work suggests that if performance is poor, and a single compartment flocculator is being used, addition of baffles should be undertaken to provide multiple compartments within the same space.

Letterman[24] discussed floc formation and breakup and the basis for tapered energy input in "Coagulation and Filtration: Back to the Basics." A high energy input at the beginning of flocculation promotes many collisions among the small coagulated particles that have entered the flocculation basin. As they travel through the basin, the floc particles grow. Larger particles need less energy for transport, and excessive energy might even break up the larger flocs. Because flocculation is believed to be dependent on both energy input and flocculation time, prevention of short circuiting is important. With completely mixed flow or short circuiting, an important portion of the coagulated water will pass through the flocculation basin in a time less than the theoretical detention time, and thus the GT input for that water will be less than desired. Jar tests can be used to develop preliminary estimates of flocculation time and energy requirements.

The need for flocculation at direct filtration plants ought to be determined on a case by case basis. For example, in order to treat cold water, flocculation was employed at a direct filtration plant in Springfield, Massachusetts[25] to provide 30 minutes of detention time after coagulants were added.

One indication of the benefit of extra detention time when cold water is treated was the change in performance of a pressure filtration package plant at Cayuga, N.Y.[26] The plant employed three pressure filtration units, the first a coarse medium, the second a multimedia filter, and the third granular activated carbon. The first unit was to promote flocculation and removal of some suspended solids. The second filter was to reduce turbidity to a fraction of 1 NTU, and the GAC unit was to remove taste-and-odor-causing substances. During times of moderate temperature, the units worked as intended, and the first two filters removed 98 to 99 percent of the turbidity-causing particulate matter. Filtered water was less than 0.20 NTU more than 50 percent of the time. During winter, however, when water temperatures were below 5°C, the percentage of turbidity removed by the coarse media filter and the multi-media filter dropped to about seventy percent. Fortunately the GAC filter did a good job of turbidity removal, and filtered water turibidy remained low. This performance may have been the result of inadequate contact time from the point of addition of coagulant chemicals to the multi-media filtration step.

Cleasby et al[27] compared direct in-line filtration with coagulation-flocculation-filtration at a gravel pit near Ames, Iowa. Conducting parallel experiments, they found that the filter receiving flocculated water had a shorter initial improvement period after backwashing, lower turbidity, and a lower rate of head loss buildup than the in-line filter, but often the filter receiving flocculated water developed turbidity breakthrough before the in-line filter did.

Although flocculation may be needed for treatment of cold water, it can be appropriate in other circumstances too. When the Southern Nevada Water System, serving the Las Vegas area, expanded its direct filtration plant from 200 MGD to 400 MGD flocculation was added to reduce alum floc carryover and PAC breakthrough.[28] The original plant was constructed to provide rapid mixing and filtration.[29] According to Monscvitz et al[28] about half of the aluminum added as alum at the flash mixers was being carried over into the finished water during in-line filtration. Also, when powdered activated carbon was added to control tastes and odors, the filtration rate was reduced from 5 gpm/sf to 2 gpm/sf to prevent the breakthrough of PAC. Pilot plant studies showed that 15 to 20 minutes of flocculation would reduce carryover of aluminum and prevent breakthrough of the PAC.

For flocculation, a variety of questions should be considered during a plant evaluation. If the plant doesn't employ sedimentation, is flocculation needed? Considering the present state of knowledge about flocculation, and the different results obtained at various locations, this question probably would be resolved best by a program of pilot testing. If flocculation is used, is baffling adequate to obtain a narrow distribution of flocculation retention times? If short circuiting is not a problem, is energy input sufficient to cause collision of coagulated particles, but not so great as to break up flocs already formed?

SEDIMENTATION

Sedimentation is a necessary treatment step when the raw water contains a large amount of particulate matter or humic substances (color), and coagulation that gives the desired finished water quality results in production of large volumes of filter clogging floc. If a sedimentation basin is in use, but seems to be ineffective, some questions are in order. One that is not so obvious is whether the design engineer selected the correct solids separation process. When soft, highly colored waters are treated for color and THM precursor removal, a light, fluffy, poorly settling floc may form. When algae are present in raw water, flocs containing algal cells may be floated to the surface of a sedimentation basin by bubbles of oxygen, a product of photosynthesis. If floc is resistant to settling, dissolved air flotation may be a more appropriate solids separation step. Flotation takes advantage of the factors that cause some flocs to resist settling.

At utility locations where the floc should settle, but it doesn't, the engineer should look for problems in settling basin design or operation. Settling theory is based upon an idealized concept in which the velocity of water in the basin is distributed uniformly, and all the water progresses from the inlet end to the outlet end of the basin. The ideal settling velocity is determined as the depth of the basin divided by the transit time from inlet to outlet.

Real world conditions, unfortunately, differ considerably from ideal. Short circuits in settling basins are a fact of life. Among the causes are effects of wind, temperature (and therefore density) differences, inlet design, and outlet design. Finding the remedies to poor settling basin behavior could require a variety of approaches.

Temperature differences and the resulting density currents might be suggested if large diurnal temperature differences are occurring. Cold nights and sunny days, and a shallow raw water source susceptible to these changing conditions, might result in rapid temperature changes in the raw water and in the treatment plant. A program of temperature measurements in raw water and at various places in the treatment plant, especially across the width and depth of the settling basin, should reveal the extent of temperature differences and indicate whether this might be a problem.

Checking a settling basin for hydraulics and flow distribution problems can be more involved. Tracer studies might be needed. Another approach could be visual observation. Hudson[2] published an aerial photograph showing clouds of floc at a settling basin inlet (p. 94). He explained that a settling basin with a poorly designed inlet might display localized clouds of floc, and that close observation of basin outlets will frequently reveal design deficiencies. When viewing of underwater objects is attempted, greater success generally is attained if the objects are viewed by looking down from above than by looking across and down into the water. Application of the "look down from above" concept would necessitate viewing settling basins from the tallest nearby structure at the waterworks, or more probably, viewing the basins from a small airplane or helicopter.

After tracer tests and visual observations are made, some physical adjustments may be necessary. If it is possible, some trial and error modifications to baffle arrangements could be attempted before permanent modifications are put in place. If baffle modifications are not sufficient, of if a higher treatment rate is needed, addition of tube settlers could be considered. Conley and Hansen[30] have discussed the addition of tube settlers to existing basins, and have provided guidance for design of tube settler installations.

As settling is evaluated, the engineer should keep in mind Walter Conley's paper, "Integration of the Clarification Process."[6] The goal of treatment is to produce the highest quality of filtered water, not the best quality of settled water that can be attained. Thus, the improvements made to settling basins, while important, do not constitute the end of the upgrading job. The filters must also be evaluated.

FILTRATION

The final, and in some plants only, step for removal of particulate matter is filtration. Improperly designed, operated, or maintained filters can contribute to poor water quality, even if pretreatment is good. On the other hand, if pretreatment is wrong, or worse yet, nonexistent, the best rapid rate filter is not going to completely salvage the situation and produce high quality filtered water. Again, the idea of integration of clarification is important. Several aspects of filtration should be investigated, including filter bed design, filter rate and rate control, filter washing and condition of the beds, hydraulics, and water quality monitoring.

Filter bed design has varied through the 1900's. Beds of sand, often with an effective size of about 0.4 or 0.5 mm, were commonly used for about half of this century. Work by Conley and Pitman,[31] by Robeck et al[32], and by Conley[6] helped to bring multi-media filter beds to the attention of engineers and water utility managers. Dual media (anthracite coal and sand) beds were used to provide larger pore spaces for storage of floc within the depth of the bed, rather than just near the surface, as with rapid sand filters. Even when operated at rates higher than conventional rapid sand filter rates, dual media filters provided excellent filtered water turbidity because of the finer layer of sand below the coal.

Both Conley and Pitman[31] and Robeck et al[32] reported on the use of polyelectrolyte to toughen the floc and control turbidity breakthrough in the latter phase of the filter run. Conley and Pitman observed that polyelectrolyte could be used with sand filters, but fine sands that produced exceptionally clear water also developed high head loss. Robeck et al[32] reported that a polyelectrolyte coagulant aid helped to achieve the optimum strength of floc, and that adequate floc strength prevented the passage of coliform bacteria, virus, carbon, or floc. Logsdon et al[17] compared different filter media configurations for turbidity and Giardia cyst removal. They also presented data on effect of chemical pretreatment on filter run length. Head loss development occurred several times faster in the sand filter, as compared to dual media. Estimated times to 8 foot head loss were 13 and 28 hours with sand filters for runs with alum and high molecular weight, slightly anionic polymer vs. four days with the dual media filters, all operating at 3 gpm/sf.

If hydraulics for filtration and backwashing permit, conversion of sand filters to dual media filters may enable a water utility to operate filters at higher rates while maintaining or improving upon effluent turbidity and lengthening filter runs. The feasibility of making such a change should be carefully evaluated by the engineer before modifications are begun. Surface wash should be provided, if it was not used with the rapid sand filter.

Dual media and later, mixed media, concepts were developed so filters would have coarser grains at the top and finer grains at the bottom after backwashing. When a bed of mixed particle sizes of uniform specific gravity is backwashed, the resulting gradation is fine to coarse from top to bottom. Use of filtering materials of different specific gravities, ranging from 1.4 for some anthracite media to 4.1 for some garnet media has brought about the desired coarse to fine gradation.

Design of multi-media beds must be approached with caution, especially if a rapid sand conversion is contemplated. In the latter situation, constraints on the backwashing rate may exist. In any case, when more than one type of filter media is used, calculations should be made to verify that the materials selected have similar fluidization velocities. Pilot plant studies can be used to verify the soundness of the design.

Cleasby[33] has suggested doing this by calculating the fluidization velocity for the D_{10} size and the D_{90} size (10% by weight smaller than D_{10} and 90% by weight smaller than D_{90}) grains for each filtering material. Fluidization velocities for each kind of small grain size should be similar. Fluidization velocities for the larger D_{90} sizes will be greater, but they too should be similar for each type of filtering material. A low uniformity coefficient will narrow the range between the fluidization velocity for coarse grains vs. fine grains of each material. The circumstance to avoid is having a multi-media filter with one layer that fluidizes at a different backwash rate from that needed by the other layer or layers. To avoid washing out the easily fluidized layer, the plant operator might have to backwash at a rate not adequate to fully clean the layer that is not so readily fluidized. Because of the difficulty associated with sampling individual materials in a multi-media filter bed that has been in use, the engineer probably will have to rely on a check of filter media specifications or visual observations of backwashing to look for problems in this area, where dual or mixed media filter beds have already been installed.

Filter rate is an important factor in determining water quality. Rate increases are especially important, because sudden increases can cause deterioration of filtered water quality. Cleasby *et al*[34] evaluated the effect of filtration rate changes on effluent quality and reported that both the magnitude of the rate increase and the rapidity of the increase were important. Gradual increases are less detrimental to quality, an important point for operators to understand. Logsdon *et al*[16] reported that an abrupt rate increase caused higher levels of turbidity and *Giardia* cysts when alum was used, but a stronger floc consisting of alum and nonionic polymer resisted breakthrough during a filtration rate increase.

Schleppenbach[5] conducted research on filtration rate increases at the Duluth Filtration Plant. Typical coagulation practice involved use of 10 to 15 mg/L of alum, about 0.10 mg/L of nonionic polymer, and pH of 6.8 to 7.3, depending on water temperature. Three rate change conditions were evaluated: 1) starting a dirty filter after shutdown overnight, going from 0 to 3.25 gpm/sf or 4.87 gpm/sf in 15 minutes; 2) going from 3.25 gpm/sf to 4.33 gpm/sf or from 4.87 gpm/sf to 6.49 gpm/sf in 60 seconds when one filter was removed from operation for backwashing; and 3) starting a clean filter and going from 0 to 3.25 gpm/sf or 4.87 gpm/sf. Both the dual media filter and the mixed media filter were restarted when clogged (9.0 ft. head loss) and in this condition about 2×10^6 amphibole fibers per liter (F/L) were detected. Slowly restarting dirty filters at lower head loss conditions did not produce this effect. Typical filter effluent during normal operation had amphibole fiber counts of 0.04×10^6 F/L or lower. Filters should be operated continuously from the beginning of a run until terminal head loss is reached, and then washed. Dirty filters should never be restarted. Logsdon et al[16] showed that *Giardia* cysts previously stored in a filter were discharged during a turbidity breakthrough, at a time when none were present in the influent water. In filtration research in which precipitated iron was the particulate matter to be removed, Cleasby et al.[34] maintained the influent iron concentration at 10 mg/L and reported peak effluent concentrations as high as 44 to 135 mg/L under instantaneous rate increases of 25% to 100%. Contaminants stored in a filter can be discharged later if the filter is operated improperly.

When a filtration plant is evaluated, typical plant operations should be observed. Pay close attention to filter start-up, rate change, and backwashing procedures. Are changes in flow made smoothly and slowly, or rapidly and in jerky steps? The latter would be detrimental to water quality. If a plant has conventional rate of flow controllers, their condition should be checked. Are they well maintained and functioning smoothly, or neglected and erratic in changes, or even unworkable? Hudson[2] noted (p. 177) that under fixed conditions rate controllers may cause surge amplitudes of 2 to 10 percent of head loss. He suggested measuring the distance between extreme levels in water piezometer tubes occurring within a one minute period, and repeating the measurements several times to obtain representative values. Water piezometers are very sensitive indicators of filter surges and thus merit study.

Other aspects of filter hydraulics are also important. Flow measurements should be made for each filter so the operator knows the actual rate of filtration. Has flow measurement capability been provided for each filter? This is not always done. If a flow measurement device exists, does it work, and when was the last time it was calibrated by a reliable method, such as one involving drawdown of water over a filter at a constant rate and over a measured time? In order for the plant operator to be in control of the filtration process, he or she must know what is going on.

If water quality is seriously degraded at the start of a new filter run, at least three remedies may be considered. The simplest approach might be to start a new run very gradually, rather than abruptly. If the filtration rate is increased uniformly from zero to the desired value over a period of time, perhaps 10 to 30 minutes, the effect of restarting after backwash may be diminished. Another approach, used by Harris[35] at the Contra Costa Country Water District, was to add nonionic polymer* to the backwash water. He indicated that initial water quality following backwash was on the order of 0.10 NTU when the filter media was preconditioned with polymer.

Chen[36] studied filter bed conditioning with polymer using the U.S. Environmental Protection Agency's Drinking Water Research Division Pilot Plant, operating it in a direct filtration mode. He reported that both turbidity and the concentration of particles in the 7 to 12 μm size range could be lowered somewhat at an 8.5 gpm/sf filtration rate and even more at a 5.0 gpm/sf rate, but some quality deterioration occurred at the beginning of the runs in nearly every run.

Amirtharajah[37] has recently completed a study of initial degradation of filter effluent quality for the American Water Works Association Research Foundation. His findings should be available in 1987.

If the above-mentioned approaches do not work, another way to improve water quality is to practice filter to waste. This might require some extensive physical modification though, and that would not be inexpensive. Filter to waste may be impractical under some conditions, even if the physical arrangement of the plant permits it. Cleasby[27] reported that when direct in-line filtration was practiced with a cationic polymer as the primary coagulant, in some runs the initial improvement period lasted several hours. Filter to waste could not be practiced for such a long time. In a case like this, a better approach would be to try to change coagulation practice so that the ripening or improvement period was drastically shortened.

During a plant evaluation, the condition of the filter beds should be noted. A filter that is about ready to be backwashed should be selected. After the water is drawn down to below the media surface, the engineer should climb down into the filter for a closer look. Is the bed level, or do obvious hills and valleys exist indicating problems of bad flow distribution during backwashing or filter operation? Does the filter surface have mud balls or caked mud? After the filter has been washed, the filter should be drawn down again so the inspection can be repeated.

---

* Magnifloc 985-N. Mention of commercial products does not constitute endorsement by U.S.EPA.

At this time the cleanliness of the media can be evaluated. Filter media should be clean after backwashing. Clean grains of sand, coal, or garnet should not be noticeably cohesive, even when wet. If filter media can be squeezed by hand into a ball, dropped on to the filter bed from waist height, and remain intact; or if filter media is spongy when squeezed into a ball, it may not be as clean as it should be to function properly.

While a filter is being backwashed the engineer should observe it carefully, watching for sand boils at the beginning of the wash. Baylis, Gullans, and Hudson[38] wrote that filter backwashing should begin slowly and with care. They felt that at least 30 seconds should be allowed to bring the backwash flow to its full value. Serious support gravel disturbances or disruption of false-bottom filter underdrains can result from sudden application of the full flow of backwash water.

The surface wash should be observed also, to verify that the water flow from the washing device is functioning as it is supposed to. Surface wash spray nozzles can become clogged during years of use. Some form of washing assistance is necessary, as backwash alone generally does not adequately clean filter media. U.S. practice generally has been to use surface wash, although air-assisted backwashing has been used successfully in some plants. Polymer floc tends to be more sticky than alum floc, so if polymers are used to assist in conditioning the raw water, careful attention to the surface wash is certainly appropriate.

A key aspect to attaining the best possible performance of filters is adequate monitoring and control. Filtered water turbidity, at a plant that practices effective coagulation, can give an indication of the efficacy of Giardia cyst removal,[16,17,39] asbestos fiber removal,[40] and of particle removal in general, even though concentrations of cysts or fibers are below the levels that can be detected by a turbidimeter. Research results suggest that when filtered water turbidity is very low, removal of cysts or fibers is effective, as is removal of light scattering particles in general. One differing view of the value of turbidity measurements has been presented by Brazos et al[41] who contend that little relationship exists between turbidity reduction and removal of total bacterial cells as determined by direct microscopic count.

Hudson[2] (p. 5) stated that much credit for improvement in water quality is due to the development of reliable water quality monitoring devices, including turbidimeters. He wrote:

> "In a number of plants, filtered-water turbidity levels prior to the initiation of turbidity monitoring were commonly held in the range of 0.2-0.5 NTU. After the initiation of monitoring, operators could observe episodes of quality deterioration and develop techniques to prevent such episodes, gradually revising their personal quality goals to new levels and commonly reducing the filtered-water turbidity to 0.02-0.05 NTU, an order-of-magnitude improvement. This process takes one to two years, but once having become accustomed to the production of water quality at such levels, the operators of these plants become intolerant of filtered water with more than about 0.06 NTU."
>
> "One of the axioms of water quality control is that, as the clarity of water is improved by improved treatment, there is a parallel reduction of color, taste and odor, bacteria and viruses,

and often of iron, manganese and alumina levels. While few consumers can detect turbidity at a level of 1 NTU except in bathtubs or swimming pools, the use of much lower levels of turbidity brings about a corollary improvement of other water quality parameters. The turbidity measurement is quick and convenient, and although it is used at levels lower than those of consumer awareness, it provides a most useful, rapid means of control of treatment processes."

A similar sentiment was recently expressed. James R. English[42] wrote in a letter to the Editor of AWWA's Mainstream that turbidity of filtered water at the Sidney N. Peterson Water Treatment Plant operated by the San Juan Suburban Water District in Roseville, California averaged 0.04 NTU. He also stated, "Achieving the levels of water quality we have has completely changed the self-image of each plant operator. They begin to worry when turbidity levels reach 0.06 NTU, and when that happens, they typically find that a drift has occurred in the chemical feed." This sounds very much like Hudson's comment on operator attitudes. Plant operators should continue to strive to find better, more cost-effective ways to treat water and improve finished water quality.

Other evidence of the attainability of very low filtered water turbidity was presented by Schleppenbach.[5] Data from the Duluth Filtration Plant (Fig. 2) show that effluent turbidity was consistently below 0.10 NTU after an initial start-up and learning period at the new plant. This occurred over all four seasons, and a range of water temperatures from 1°C to about 12°C.

A key to the success at Duluth, and an approach used by many filtration plants, is the continuous monitoring of effluent turbidity. Conley[6] stated, "Continuous monitoring of filter plant effluent with sensitive turbidimeters is essential for intelligent management of the plant." A similar opinion was held by Robeck et al[32] who wrote, "Of course, monitoring for turbidity passage on a continuous, or half hour interval, basis also allows the operator to know the status of the filters and the influence of chemical dose changes."

"Intelligent management", and "knowing the status" are the key words. When turbidity is monitored consistently, operators are able to observe trends in turbidity, and changes can be detected and acted upon soon after they occur. The operator is not put in the position of knowing what the turbidity is only once every two, four, or eight hours, as might be the case if turbidity was measured only in grab samples taken to the laboratory for analysis. Note that for compliance purposes the latter approach may be preferred, and that grab sample measurement is often used simultaneously with continuous turbidity measurement as a means of adjusting the calibration of continuous flow turbimeters. When turbidimeters are installed at all filters, readout devices can be placed in operational control panels so that the operator has instantly available information. Chart recorders can be used to provide written records.

When a filtration plant is inspected, the engineer should pay careful attention to the sampling points for filtered water turbidity, to sample handling, and to instrument calibration. To really be able to control filter operation, with respect to water quality, the plant operator should be able to sample each filter effluent flow stream independently, at a point where there has been no mixing with water from any other filter. Although sampling at a point of entry into the distribution system (e.g. clearwell effluent) is required by the turbidity regulation, clearwell sampling reveals very little about the specific condition of an individual filter, because of the blending that occurs in the clearwell.

Sample handling and analysis are important. Turbidity samples should be taken to the laboratory promptly if grab samples are to be analyzed. The sample cell must be scrupulously clean when it is inserted into the turbidimeter, and there should be no air bubbles in the sample. This can be a problem when the water is cold. Turbidimeters should be calibrated with secondary standards as often as instrument manufacturers and experience indicate (whichever is shorter), and with formazin or some other approved primary standard as frequently as required by Standard Methods or the EPA Methods Manual. Note that most improper practices in handling low turbidity water samples would cause the turbidity measurement to be higher. Careful handling and measurement of grab samples may reveal that filtered water turbidity is actually lower than it was thought to be when sufficient analytical precautions were not taken.

CLEARWELL

Although water in the clearwell has already been treated for removal of particulate matter, the job of treating surface water is not completed until disinfection has been accomplished. One aspect of disinfection practice that is related to treatment plant evaluation and improvement is disinfectant contact time. The concept of attaining plug flow and eliminating short circuiting is as important in the clearwell as in the flocculation and sedimentation basin, or maybe even more important. The same concepts discussed eariler apply here. A tracer study should be conducted to determine the distribution of actual residence times in the clearwell. This is especially important at utilities that do not have long transmission lines to town and thus rely on the clearwell for an important portion (or all) of the disinfectant contact time. Water utility engineers should become familiar with the design concepts used in chlorination contact chambers at wastewater treatment plants. The baffles used at clearwells might not need to be so elaborate as those at wastewater treatment plants, but it is likely that clearwells often were designed with water storage, rather than assured contact time, as the primary function.

Lippy[43] presented an interesting example of theoretical detection time vs. actual flow-through time in a review of a giardiasis outbreak in New Hampshire. The treatment plant had a 0.5 million gallon storage facility plus a 0.04 million gallon pumping well that followed the postchlorination injection point. Based on volume displacement calculations and the plant production rate, the 0.54 million gallons should have provided 7 hours of contact time. In actual practice, a substantial boost in chlorine dosage was followed by a measurable increase in chlorine concentration in water discharged from the pumping well in only 1-3/4 hours. Contact time is not always what it appears to be, as calculated by basin volume and flow rate. Actual contact time as measured in a tracer study should be used to evaluate disinfection practice.

LABORATORY AND PILOT FACILITIES

One interesting aspect of coagulation and filtration is that the water quality information and the level of operator skill, including understanding of water chemistry, needed to attain optimum treatment of the water are essentially the same regardless of plant size. This does not mean that all plants are equipped or staffed at the same level. Rather, water chemistry principles apply to treatment in a jar test or pilot filter just as they apply at a very large plant.

Unfortunately, very small treatment plants may not have budgets adequate to support one or more operators with sound training in the concepts of water chemistry that need to be understood to assure that coagulation practice is correct at all times, and the available equipment for process evaluation and control may be quite limited. When a plant is evaluated the engineer should remember that even the best facility design may not function well if the operator does not understand how to control the plant, if equipment is neglected and not working, or if the amount of operator time available each day is simply inadequate for process control. Problems related to inadequate human or equipment resources need to be discussed with water utility management.

At water utilities that are large enough to have full time operators and adequately equipped laboratories, the engineer should evaluate the level of plant personnel, as well as the extent of testing, water quality evaluation, and quality control carried out in the laboratory and pilot facilities. Laboratory equipment should be used for coagulation control and process evaluation as frequently as appropriate, at the given site. Conditions that suggest a need for testing and evaluation include changes in raw water alkalinity, pH, temperature, turbidity, color, and algae concentration. Changes in behavior of settling basins and changes in filtered water turbidity would indicate a need to reevaluate coagulant chemical feed. Check to verify that appropriate testing has been done in the past.

Some water filtration plants are equipped with pilot filters, and a few have pilot plants that can be used to evaluate treatment processes carefully before they are implemented on a full scale basis. The advantage of the pilot plant is that testing can be done, and if a treatment approach that appeared promising in jar tests does not prove acceptable in a flow-through mode, the water can be wasted. If a change is made in the plant and it proves unsuccessful, at most plants the results of the failure have to be sent to the distribution system. It is better not to have to make unverified major changes at full scale.

Pilot plants offer important advantages in addition to confirming jar test results. Experimentation is cheaper at the pilot scale than at full scale, in terms of water used and wasted and chemicals fed. Pilot plants make excellent training facilities, because they can be used to demonstrate problems that might occur in a full scale plant. For example, the effect of loss of coagulant feed can be shown, and the treatment approach for unusually high raw water turbidity can be explored. For turbidity removal studies, spiking raw water with fine sediment obtained near the raw water intake would be appropriate. If this is impractical, try to obtain soil or sediment typical of that which runs off into the stream or river or is stirred up from the lake bottom, causing the turbidity to rise substantially and creating problems for the treatment plant. Try to use native materials rather than clay purchased from some distant source.

A pilot plant can be an important morale booster as well as training tool. Operators who can keep filtered water quality under control in a pilot plant even when conditions are adverse, should be confident of their ability to manage the full scale plant under a wide variety of conditions, and this confidence should be reflected in consistently high water quality if the physical facilities are in reasonably good condition.

PLANT IMPROVEMENT EXAMPLES

Many examples of treatment plant upgrading have appeared in the AWWA literature. Examples include "Upgrading Existing Water Treatment Plants,"[44] "Upgrading Water Plants to Improve Water Quality,"[45] the September 1981 issue of Journal AWWA, which had the theme of "Upgrading Treatment Plants," and Water Clarification Processes: Practical Design and Evaluation, by Hudson. This manuscript contains brief descriptions of water quality improvement efforts at four filtration plants.

Information on improvements at two plants in Michigan was provided by Erickson.[46] Plant G, a 3 MGD facility, has an upflow clarifier designed for a 1 gpm/sf rise rate, and mixed media filters with a design rate of 3 gpm/sf. The plant is normally operated at about two-thirds capacity. Raw water turbidity is generally less than 5 NTU, color ranges between 5 and 50 units, and temperature varies between 2°C and 15°C.

In 1973, after the plant had been in operation for three years, the plant staff relocated the liquid alum application point to a downstream tee on the low lift pump header. Performance improved, and coagulant use decreased about one-third, because of the enhanced mixing and injection in the centerline of pipe flow. In 1986, the staff fabricated a baffled orifice device that creates about 10 feet of head loss in a pipe with a 6 ft/sec velocity. Alum now is injected in the center of the flow stream, just upstream of the orifice. This change is believed to have reduced coagulant consumption an additional 20 percent.

Another facility (Plant M) described by Erickson[46] is a conventional coagulation plant, having raw water with turbidity generally below 5 NTU, color of 5 to 20 units, and temperatures of 0° to 25°C. This plant is old, and employs a rising well for coagulant mixing, baffled-flow flocculation (no mechanical stirring), sedimentation, and sand filters rated at 2 gpm/sf. Although rated at 4 MGD, typical operation is about 1.5 MGD.

This plant was modified in 1977 to improve chemical mixing. Alum solution feed was relocated from the rising well to the volute of a low lift pump that was always used. This resulted in a much more intense and rapid distribution of the coagulant throughout the raw water. This improved mixing allowed the plant to lower chemical usage by about 25 percent, while at the same time improving plant performance as measured by color removal and filtered water turbidity.

Extensive improvements to Plant M in Pennsylvania were described by Ashton.[47] This is an old 9 MGD conventional plant with a rising well for chemical mixing, baffled-flow flocculators, settling basins, and 0.92 mm effective size anthracite filters that were designed for 2 gpm/sf. Raw water turbidities encountered typically range from 2.5 to 200 NTU.

After the community experienced a giardiasis outbreak, a number of improvements were made. Filters were checked to make sure they would not be operated above 2 gpm/sf. Baffles were installed to slow down the flow of settled water after it entered the filters. A velocity jet had scoured some media at the end of some filters before this change was made. A program of raking media once a week to help prevent mud accumulation was undertaken, because the plant had no surface wash equipment. A six inch layer of 0.45 mm sand was placed on top of the anthracite media in each filter, and the bed was then backwashed. This created dual media filters in a plant that had been originally equipped with sand filters. On-line monitoring for turbidity of settled and finished water was installed. A major improvement was addition of a streaming current detector for control of the coagulation process. Addition of lime with alum was eliminated. Alum coagulation at a pH of 6.6 to 6.8 is now practiced.

The changes collectively have enabled plant M to lower its finished water turbidity from a previous average of 0.4 to NTU to $\leq$ 0.05 NTU. Better process control has been attained also. A raw water turbidity increase from 6 NTU to over 200 NTU in only 6 hours resulted in a change in finished water turbidity from 0.03 NTU to 0.05 NTU and demonstrated the capability of this improved plant to cope with wide ranges in turbidity.

In February, the author evaluated Plant C during a waterborne disease outbreak caused by <u>Cryptosporidium</u>, a protozoan parasite that may be very resistant to chlorine. Plant C was a conventional plant with rapid mixers of the back mix type, flocculation basins designed for mechanical stirring, sedimentation, and anthracite-sand filters designed to be operated at 2 gpm/sf. This plant employed alum coagulation. In the two month period prior to and during the outbreak, raw water turbidity generally ranged from 12 to 30 NTU. After the outbreak was under way, a large storm caused raw water turbidity to increase to over 200 NTU, but finished water turbidity did not increase above 1 NTU.

During the plant evaluation, the author noted some physical features and some operating procedures that needed improvement. The original reel-type flocculators had been removed and axial flow flocculators were being installed. Before and during the outbreak, no mechanical agitation was provided in the flocculation process. In addition, the filter head loss instrumentation was not working, nor was the monitoring system that had been used to measure turbidity from each filter.

A signifiant factor in plant operation was the practice of shutting off some filters when water production exceeded demand, and then restarting them without backwashing when increased water production was needed. This was done on the evening of February 3, when three filters with 36 to 37 hours of operating time were restarted at 6:00 PM without backwashing. Turbidity in the dirty filters ranged from 0.20 to 0.86

NTU in filter 3, 0.41 to 2.8 NTU in filter 8, and 1.6 to 3.2 NTU in filter 10 over a period of three hours. That same evening, turbidity in four other filters that had been operating between 29 and 30 hours ranged from 0.07 to 0.18 NTU. The deleterious effect of restarting dirty filters was obvious. At noon on February 5, after most of the filters had been backwashed that day or the day before, turbidity from

individual filters ranged from 0.05 to 0.16 NTU for filters that had been in operation from 11 to 18 hours. A turbidity of 0.46 NTU was observed on one filter with 57 hours of operation since backwash. The experience at plant C showed the value of carefully evaluating operating procedures as well as monitoring the turbidity of each filter. The procedural change (not restarting dirty filters) resulted in a significant improvement in water quality.

The above examples indicate that even small or moderate changes in plant facilities, monitoring instruments, or operating procedures can yield lower filtered water turbidity.

ACKNOWLEDGEMENT

The author wishes to acknowledge the filtration expertise of the late Herbert E. Hudson, Jr., Walter R. Conley, John L. Cleasby, and Gordon G. Robeck. Their published works, and the personal influence of Mr. Robeck, have influenced much of the thought that produced this paper.

REFERENCES

1. Baumann, E. R. Direct Filtration of Lake Superior Water for Asbestiform Fiber Removal; Appendix I, Diatomite Filters for Asbestiform Fiber Removal from Water. EPA-670/2-75-050g, U.S. Environmental Protection Agency, Cincinnati, Ohio (1975).

2. Hudson, H. E., Jr. Water Clarification Processes: Practical Design and Evaluation. Van Nostrand Reinhold Company, New York (1981).

3. Lippy, E. C. Engineering Aspects of Waterborne Outbreak Investigation, in Waterborn Diseases in the United States, G. F. Craun, Ed., CRC Press, Boca Baton, Florida (1986).

4. Standard Methods for the Examination of Water and Wastewater, 16th Ed., American Public Health Association, Washington, D.C. (1985).

5. Schleppenbach, F. X. Water Filtration at Duluth. EPA-600/2-84-083, U. S. Environmental Protection Agency, Cincinnati, Ohio (1984).

6. Conley, W. R., Jr. Integration of the Clarification Process. Jour. AWWA, 57:10:1333 (Oct. 1965).

7. Edzwald, J. K. Coagulation. In: Coagulation and Filtration: Back to the Basics, AWWA Seminar Proceedings, No. 20155 (June 1981).

8. Wagner, E. G., and Hudson, H. E., Jr. Low-Dosage High-Rate Direct Filtration. Jour. AWWA, 74:5:256 (May 1982).

9. Neuman, W. E. Optimizing Coagulation with Pilot Filters and Zeta Potential. Jour. AWWA, 73:9:472 (Sept. 1981).

10. Griffith, J. D., and Williams, R. G. Application of Jar Test Analysis at Phoenix, Arizona. Jour. AWWA, 64:12:825 (Dec. 1972).

11. Moffett, J. W. The Chemistry of High-Rate Water Treatment. Jour. AWWA, 60:11:1255 (Nov. 1968).

12. Hudson, H. E., Jr., and Wagner, E. G. Conduct and Uses of Jar Testing. Jour. AWWA, 73:4:218 (April, 1981)

13. American Water Works Association Research Foundation, Evaluation of On-Line Instrumentation for Continuous Chemical Dose Control. University of Delaware, S. Dentel, Principal Investigator.

14. Conley, W. R., and Evers, R. H. Coagulation Control. Jour. AWWA, 60:2:165 (Feb. 1968).

15. Kreissl, J. F., Robeck, G. G., and Sommerville, G. A. Use of Pilot Filters to Predict Optimum Chemical Feeds. Jour. AWWA, 60:3:299 (March 1968).

16. Logsdon, G. S., Symons, J. M., Hoye, R. L., Jr. and Arozarena, M. M. Alternative Filtration Methods for Removal of Giardia Cysts and Cyst Models. Jour. AWWA. 73:2:111 (Feb. 1981).

17. Logsdon, G. S., Thurman, V. C., Frindt, E. S., and Stoecker, J. G. Evaluating Sedimentation and Various Filter Media for Removal of Giardia Cysts. Jour. AWWA, 77:2:61 (Feb. 1985).

18. Hudson, H. E., Jr., and Wolfner, J. P. Design of Mixing and Flocculating Basins. Jour. AWWA. 59:10:1257 (Oct. 1967).

19. Forbes, R. E., Nickerson, G. L., Hudson, H. E., Jr., and Wagner, E. G. Upgrading Water Treatment Plants: An Alternative to New Construction. Jour. AWWA, 72:5:254 (May 1980).

20. Weston Water Utility, Schofield, Wisconsin. Control of Asbestos Fiber Loss from Asbestos-Cement Watermain. EPA-600/2-84-014, U.S. Environmental Protection Agency, Cincinnati, Ohio (1984).

21. Letterman, R. D., Quon, J. E., and Gemmell, R. S. Influence of Rapid Mix Parameters on Flocculation. Jour. AWWA, 65:11:716 (Nov. 1973).

22. Vrale, L., and Jorden, R. M. Rapid Mixing in Water Treatment. Jour. AWWA, 63:1:52 (Jan. 1971).

23. Argaman, Y., and Kaufman, W. J. Turbulence and Flocculation. Jour. of the Sanitary Engineering Div., ASCE, 96:2:223 (April 1970).

24. Letterman, R. D. Flocculation. In: Coagulation and Filtration: Back to the Basics, AWWA Seminar Proceedings, No. 20155 (June 1981).

25. Sweeney, G. E., and Prendiville, P. W. Direct Filtration: An Economic Answer to a City's Water Needs. Jour. AWWA, 66:2:65 (Feb. 1974).

26. MacNeill, J. S., Jr., and MacNeill, A. Feasability Study of Alternative Technology for Small Community Water Supply. EPA-600/2-84-191, U.S. Environmental Protection Agency, Cincinnati, Ohio (1985)

27. Cleasby, J.L., Hilmoe, D. J., Dimitracopoulos, C. J., and Diaz-Bossio, L. M. Effective Filtration Methods for Small Water Supplies. EPA-600/2-84-088, U. S. Environmental Protection Agency, Cincinnati, Ohio (1984).

28. Monscvitz, J. T., Rexing, D. J., Williams, R. G., and Heckler, J. Some Practical Experience in Direct Filtration. Jour. AWWA, 70:10:584 (Oct. 1978).

29. Spink, C. M., and Monscvitz, J. T. Design and Operation of a 200-MGD Direct Filtration Facility. Jour. AWWA, 66:2:127 (Feb. 1974).

30. Conley, W. R., and Hansen, S. P. Advanced Techniques for Suspended Solids Removal, in Water Treatment Plant Design For the Practicing Engineer, R. L. Sanks, Ed., Ann Arbor Science Publishers, Ann Arbor, Michigan (1978).

31. Conley, W. R., and Pitman, R. W. Test Program for Filter Evaluation at Hanford. Jour. AWWA, 52:2:205 (Feb. 1960).

32. Robeck, G. G., Dostal, K. A., and Woodward, R. L. Studies of Modifications in Water Filtration. Jour. AWWA, 56:2:198 (Feb. 1964).

33. Cleasby, J. L. Unconventional Filtration Rates, Media, and Backwashing Techniques. In: Innovations in the Water and Wastewater Fields, E. A. Glysson, D. E. Swan, and E. J. Way, Eds. Butterworth Publishers, Boston (1985).

34. Cleasby, J. L., Williamson, M. M., and Baumann, E. R. Effect of Filtration Rate Changes on Quality. Jour. AWWA, 55:7:869 (July 1963).

35. Harris, W. L. High-Rate Filter Efficiency. Jour. AWWA, 62:8:515 (Aug. 1970).

36. Chen, Cheng-Tyng. Filter Preconditioning to Reduce Initial Degradation in Effluent Water Quality. Master of Science Thesis submitted to University of Cincinnati, Cincinnati, Ohio (1986).

37. AWWA Research Foundation, Evaluation of Contamination Potential of Filter-to-Waste Procedures at Filter Plants. Contract with Montana State University, Dr. A. Amirtharajah, Principal Investigator.

38. Baylis, J. R., Gullans, O., and Hudson, H. E., Jr. Filtration, In: Water Quality and Treatment, Third Edition, American Water Works Association (1971).

39. Al-Ani, M. Y., Hendricks, D. W., Logsdon, G. S., and Hibler, C. P. Removing Giardia Cysts from Low Turbidity Waters by Rapid Rate Filtration. Jour. AWWA, 78:5:66 (May 1986).

40. Logsdon, G. S., and Symons, J. M., and Sorg, T. J. Monitoring Water Filters for Asbestos Removal. Jour. of the Environmental Engineering Division, ASCE, 107:6:1297 (Dec. 1981).

41. Brazos, B. J., O'Connor, J. T., and Lenau, C. W. Seasonal Effects on Total Bacterial Removals in a Rapid Sand Filtration Plant. Presented at Poster Session, 1986 AWWA Water Quality Technology Conference, Portland, Oregon (Nov. 16-19, 1986).

42. English, J. R. Meeting Turbidity Standards, Letter to Editor of AWWA Mainstream, 31:1:2 (Jan. 1987).

43. Lippy, E. C. Tracing a Giardiasis Outbreak at Berlin, New Hampshire. Jour. AWWA, 70:9:512 (Sept. 1978).

44. Upgrading Water Treatment Plants to Improve Water Quality. Proc. AWWA Seminar, No. 20153. Presented at the AWWA Conference (June 15, 1980).

45. Upgrading Existing Water Treatment Plants. Proc. AWWA Seminar, No. 20126. Presented at the AWWA Conference (June 15-16, 1974).

46. Erickson, J. Letter to G. S. Logsdon, January 30, 1987.

47. Ashton, J. P. Letter to G. S. Logsdon, February 3, 1987.

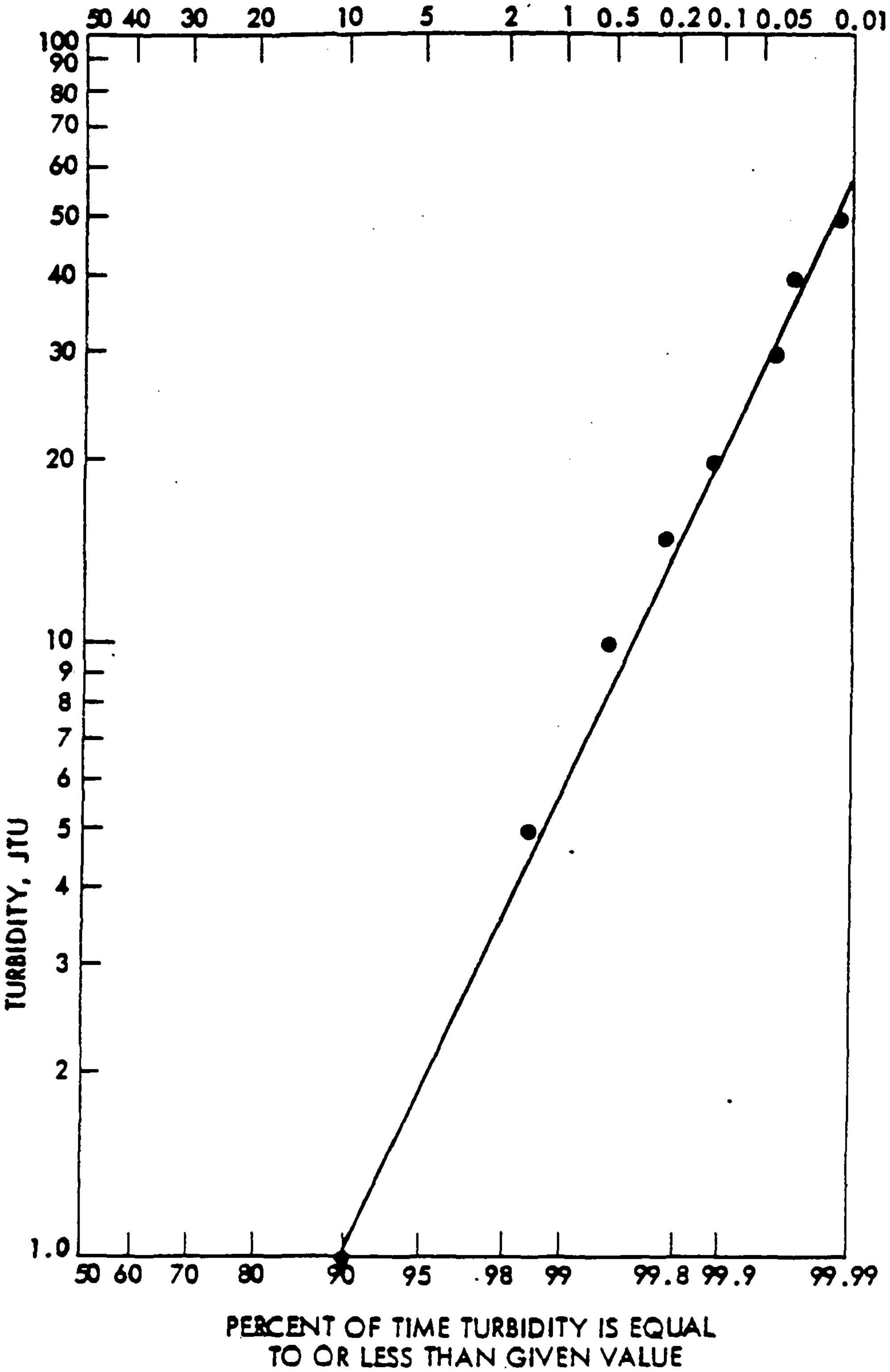

Fig. 1. City of Duluth, Minnesota, Lakewood Pumping Station, Lake Superior raw water turbidity, 1952-1972.

(From Baumann[1])

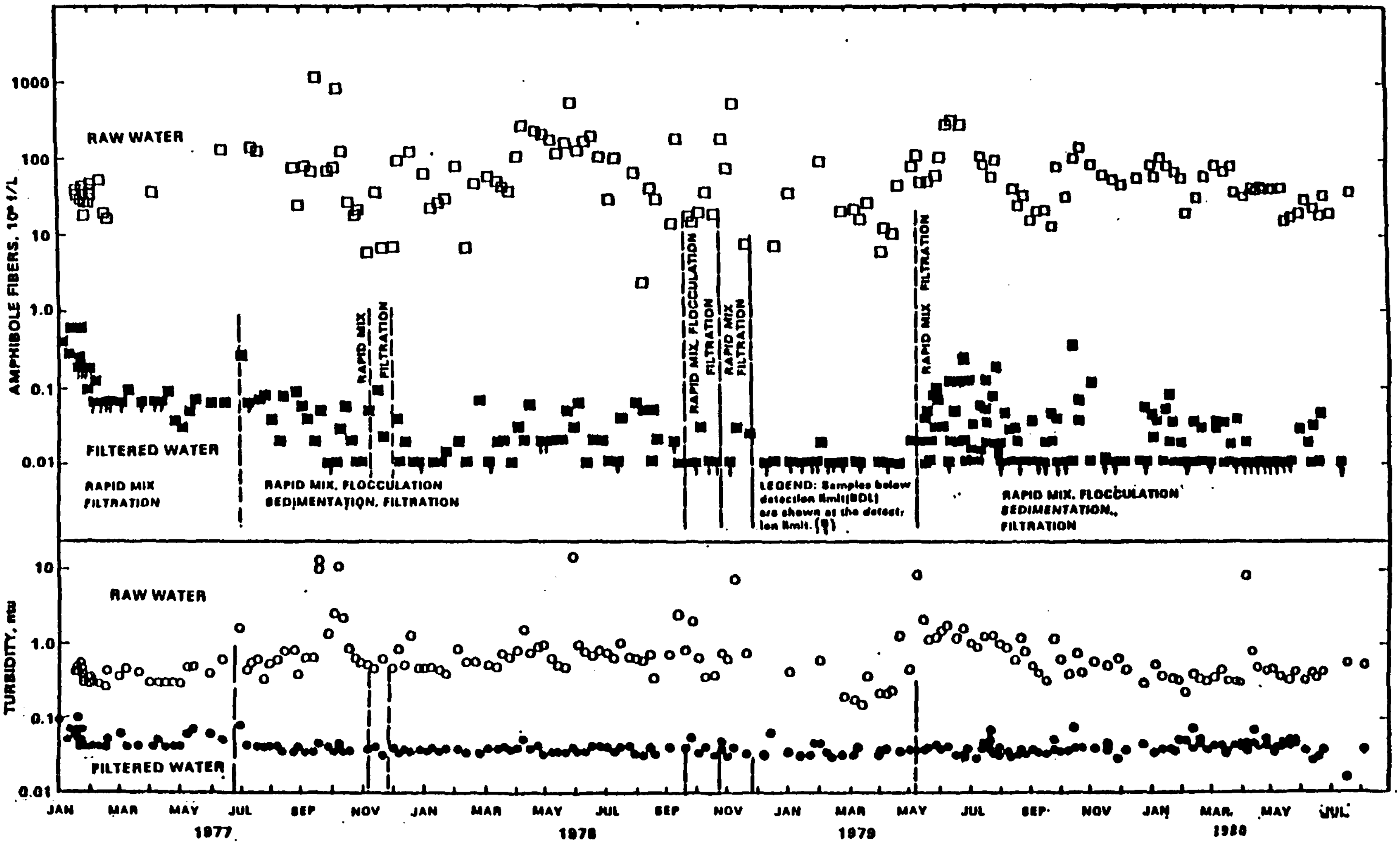

Fig. 2 Raw and Filtered Water Quality at Duluth, MN