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UNIVERSITY OF ALBERTA

DRINKING WATER FILTRATION:
ANALYSIS, DESIGN AND IMPROVEMENT

BY

SUPRAMANIAM SUTHAKER ©

A THESIS SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND
RESEARCH IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE
DEGREE OF DOCTOR OF PHILOSOPHY

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FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled Drinking Water Filtration: Analysis, Design And Improvement submitted by Supramaniam Suthaker in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Environmental Engineering.

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18 Dec 95

Dr. D. Mavinic
(University of British Columbia)

To

My Parents,

My Wife Nagula,

&

To My Teachers.

ABSTRACT

With the advancement of knowledge in drinking water and related health impacts, requirements for drinking water have progressively become more stringent. A pilot-scale study was conducted to select new media to upgrade the filters at the Rossdale Water Treatment Plant in Edmonton, Alberta, Canada in order to meet a new more stringent turbidity regulation. Based on the screening test results, the performance of crushed quartz mono-media, anthracite/rounded sand dual-media, and the existing filter sand was assessed by in-depth investigation of factors such as filtration rate, filter run length, resistance to hydraulic transients, polymer addition and filter ripening sequence. Filter performance was analyzed using different statistical methods.

In terms of filter ripening and turbidity removal at the filtration rates used, crushed quartz performed the best overall. Abrasion resistance tests such as friability, changes in particle size distribution and acid solubility were performed to assess the media durability. Scanning electron microscopy was used to explore the characteristics such as surface cracks, pores, particle accumulation on the media surface. Results indicated that the crushed quartz was resistant to abrasion and should retain its angularity. Results from filter ripening studies indicated that starting filtration rate of 8 m/h was optimum for reducing the filter ripening sequence. An optimum filtration rate exists which minimized the volume of water wasted during the filter-to-waste procedure. The influent solid flux rate can be used to optimize the filter ripening better than using the influent turbidity.

Negative power transformations were required to normally distribute the observed data (effluent turbidity, filter run length and water production capacity) from which legitimate inferences about filtration could be made. A confidence level-based probabilistic model was used to estimate reliability of filter operations. Design values for filtrate

turbidity, filter run length and water production capacity were estimated from the model. In situations where the boundary conditions are not the same as in this study, the data transformation and the design procedures presented in this study could be used in conjunction with the results of short-term pilot tests.

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Introduction

1.1 Statement of the Problem

Conventional drinking water treatment for particle removal consists of coagulation, flocculation, sedimentation, and filtration. The first two treatment processes condition the particles in the water to enhance their removal by sedimentation and filtration. When turbid waters treated with a coagulant are settled, the majority of the particulate matter can be removed. Filters can then produce a low turbidity effluent and produce more water during a filter cycle.

With the increasing knowledge of the health impacts of microbial contaminants in drinking water, more emphasis is now given to particle removal with the intention of microorganism removal. One of the better known is Giardia *lamblia*, a flagellated protozoan that causes waterborne intestinal disease. Approximately 50 percent of the identified waterborne disease cases are attributed to *Giardia* (LeChevallier et al. 1990). *Cryptosporidium* is another protozoan identified as an agent to cause clinical illness in human and animals (LeChevallier et al. 1990). Both protozoa produce environmentally stable cysts that allow for the extended survival of the parasites in surface water and treated drinking water. Nieminski and Ongerth (1995) indicated that the data on *Giardia* cyst and *Cryptosporidium* cyst removal correlated with the removal of particles of each cyst's size range. Filtration is the last physical treatment step in conventional water treatment plants for the removal of particulate matter. Therefore, proper filter operation and monitoring are essential to control microbial contamination of drinking water.

The turbidity of water is used to measure the particulate material in the water and is characterized by a nephilometric measurement (measuring the intensity of the light scattered at 90° to the path of incident light). The particulate matter may also be a source of nutrients and protection for some microorganisms. Due to concerns with protozoan cysts in drinking waters, maintaining low number of 1 to 10 μm particles as measured by the turbidity in filtered waters has become important in water treatment. Even at finished water turbidities of less than 0.1 NTU (nephilometric turbidity unit), *Cryptosporidium* cysts can exist, posing a risk (Miller, 1994). Turbidity measurements were initially used to maintain aesthetic water quality. Now, they are used to justify pathogen removal credits of the Surface Water Treatment Rule in the United States (Letterman, 1994). One of the recommendations for the control of microbial contamination in drinking water was to continuously monitor the filtered water turbidity by the installation of continuous recording turbidimeters (Bellamy et al. 1993).

Concerns about the relationship between microbiological quality of the drinking water and turbidity have lead to more stringent effluent turbidity guidelines and standards. Current Canadian and U.S. standards suggest that filtered water turbidity should be less than 1 NTU. However, recent research recommends maintaining a filtered water turbidity less than 0.2 NTU (Nieminski and Ongerth, 1995) for effective removal of *Giardia* and *Cryptosporidium* cysts. The new effluent turbidity requirements are difficult to be achieved in many filtration plants which were not designed for treatment to the lower turbidities required. Improving the performance of a filtration plant that does not meet the turbidity standards may become a more common activity with the implementation of more stringent turbidity requirements. Plant improvements and optimization of plant operations can be effective in lowering the turbidity of the filtered water. In view of the removal of microorganisms in drinking water, a recent study (Bellamy et al. 1993) has made recommendations which states:

> *"To provide the most effective barrier possible against Cryptosporidium and Giardia cysts, water utility managers should look at their facilities and operating procedures with the objective of improving water quality of treated water as much as feasible."*

> *"Funds spent on process improvements can help to buy not only better water quality but also the peace of mind that comes from not having an outbreak to contend with."*

Filtration process improvements should result in better water quality. Since water quality is measured by turbidity, such improvement should reduce the finished water turbidity. Some of the major factors influencing the overall quality of filtered water are the raw water quality, pretreatment, filter ripening, avoidance of sudden rate changes, choice of filter control scheme, use of coagulants as filter aid, and effective backwashing (Amirtharajah, 1988). In addition, using a better filter media type will help improve filtrate quality. Based on plant experiences, Fulton (1987) recognized some factors, which inhibit upgrading existing filtration plants to meet stringent standards, such as: i) inadequate hydraulic design affecting flow distribution between parallel treatment units; ii) short circuiting of flow through pretreatment mixing, flocculation and settling, and; iii) poor maintenance of mechanical equipment, instrumentation controls and filter media. With proper application of filter design to accommodate plant operating and physical conditions, existing water treatment facilities can be effectively upgraded. Pilot plant experiments are very valuable in achieving such goals.

Existing mathematical models do not allow the estimation of finished water quality based on filter operating parameters. Therefore, pilot scale experiments with the actual filter media and the plant influent water are often recommended for the assessment of filter performance (Davis, 1983). Filtration pilot plants are influenced by the influent quality which depends on the raw water characteristics and the performance of the pretreatment units of a treatment plant. Reliability of the pilot plant results is an important factor because the results are susceptible to the fluctuations in the pilot plant influent. Therefore, reliability-based design criteria, using statistical concepts, become essential for comparing pilot plant results in view of the water quality standards.

This research program was initiated by the need for upgrading the filter performance at the Rossdale water treatment plant in Edmonton, Alberta, Canada. The treatment train at the Rossdale water treatment plant includes lime softening, in addition to conventional water treatment processes, before the water is filtered. Many alternatives are available for the improvement of filtration performance and for the provision of excellent quality of drinking water. The improved performance can be achieved by: i) replacing the filters with better filter media; ii) optimizing the operating conditions of the filters; and iii) estimating the reliability of filter performance that could be used to design filters in terms of the standards and guidelines for filtered water turbidity.

The study presented in this thesis included the above aspects of improving filtration to meet and exceed the more stringent water quality standards for turbidity values. Specific research objectives are presented at the end of this chapter (Section 1.3). Relevant literature has been presented in each chapter. The following section describes some aspects of filtration related to drinking water quality improvement.

1.2. Aspects of Filtration

1.2.1 Filtration Mechanisms

1.2.1.1 Particle Transport

Removal of suspended particles occurs in two steps: the transport across the flow stream within the filter bed and the attachment to the media which are also called collectors. The transport of particles in the pores of the media is the combined effects of bulk velocity, diffusion and sedimentation (Habibian and O'Melia, 1975). Transport by diffusion arises from random Brownian motion caused by the bombardment of the particles by molecules of water. Sedimentation is caused by the gravity force and associated settling of particles across the streamlines to reach the collector. Particle and fluid densities and viscosity predominantly influence sedimentation. The transport mechanisms generally depend upon the characteristics of the suspended particles to be removed, the filter media and the flow regime of the filter. Principal factors which influence the transport mechanisms are the suspended particle size, their density and shape, the surface area and pore volumes of the filter bed, filter media shape and size, the filtration rate, temperature and the viscosity of water. Another important consideration relative to transport mechanism is the hydrodynamic retardation which is the resistance by the water which should move away as the particle approaches the collector. Hydrodynamic retardation becomes increasingly important as the fluid viscosity increases.

1.2.1.2 Particle Removal

The principal mechanisms of particle removal within a granular-media filter are identified as straining, sedimentation, impaction, interception, adhesion, chemical adsorption, physical adsorption and flocculation (Tchobanoglous and Eliassen, 1970). Some of the above mechanisms have been illustrated by Figure 1.1 and Figure 1.2. The straining mechanism can arise from either mechanical straining as described above or by chance contact where particles smaller than the pore space are trapped within the filter by chance (Tchobanoglous and Eliassen, 1970). As the pores become smaller due to the deposition of particles, the size of the particles removed by straining becomes smaller. Impaction mechanism is the removal of heavier particles that deviate from streamlines to come into contact and be removed from water by the collectors. Interception occurs when the particle moves along a streamline sufficiently close to the collectors for attachment to occur (Amirtharajah, 1988). Some of the flocculant particles which are attached to the collectors by adhesion are sheared away before they are firmly attached and pushed deeper into the filter bed.

Physical attachment of the transported particles to the surface of the media is necessary for them to be trapped by the filter. Surface-interaction forces in granular media filtration depend on the physical and chemical properties of the interacting surfaces and can affect the particle removal efficiency. The attachment mechanisms involve either electrostatic interactions, van der Waal's forces or surface chemical interactions (O'Melia and Stumm, 1967). Two models for particle attachment mechanisms such as the 'double layer model' and the 'bridging model' are available. The double layer model is based on the interaction between the electrostatic repulsive forces. The double layer force arises from the tendency of particles in an aqueous environment to acquire surface charge. The surfaces of particles in natural water and the surface of the filter media tend to carry net negative charges.

The bridging model is based on the interactions by chemical bonding and bridging of the suspended particles through reaction with the coagulant/flocculant (Adin and Rebhun, 1974). A polymer is often added as filter aid. The polymer molecules adsorb on the particle or collector surface and extends beyond the effective limit of the diffuse layer. If the free end of polymer chain contacts the other surface, particle attachment in the form of bridging occurs with minimal intermixing of diffuse layers. Bridging is mainly influenced by molecular forces formed by polymers or by the hydrolysis products of iron and aluminum which are added to the influent during coagulation, but it is influenced significantly by chemical and physical variables such as the ionic composition and pH of the water, the type and dose of coagulant, the type of influent particles to be removed, and the surface condition of the filter media.

Carry-over coagulants from pretreatment and/or those added as filter aid may utilize the eddy currents and the mixing within the pores of the media to flocculate the particles into larger particles which are more easily removed (Willson and Lekkas, 1980). Ellis (1985) suggested that the biological activity within the top part of the slow sand filter bed is an important factor in particle attachment. Abrasion of filter media during frequent filter backwash prevents or minimizes biological activity in rapid sand filtration. Besides, due to unwanted risk of microbial contamination, biological activity may not be preferred in drinking water filtration. Out of the above filtration mechanisms, straining, sedimentation, impaction, interception, adhesion and chemical adsorption are the predominant mechanisms in granular media filtration (Metcalf and Eddy, 1991).

The particle detachment mechanisms are also an important consideration in filtration. Detachment of particles occurs when the forces causing the particle attachment to the collectors are overcome by the shear forces of water flowing through the interstitial spaces within the filter bed. The magnitude of particle detachment depends on hydrodynamic forces, deposit morphology, influent particle concentration and particle type. It should be noted that the mechanisms of particle attachment and detachment occurs simultaneously and the detachment mechanism often controls the effluent particle concentration and particle size distribution as a significant portion of particles in the effluent arise from the detached particles or flocs (Ginn et al. 1992).

1.2.2 Use of Coagulants as Filter Aid

Filter aids prevent premature turbidity breakthrough by controlling floc penetration into the filter. Traditionally, polymers can be categorized into three groups, viz., anionic, cationic and non-ionic polymers. Polymers which have preponderance of negative sites are called anionic and that of positive sites are called cationic. Non-ionic polyelectrolytes, which have a balance of negative and positive sites, are very useful in maximizing the performance of high-rate filtration systems. Polymers are available as high and low molecular weight and with different structure and charge density. Typical filter aid dosages are from 0.02 to 0.1 mg/L (Smith et al. 1991). Operating experiences from water treatment plants (Cleasby et al. 1989; Amirtharajah and Kawamura, 1983) revealed that a majority of lime softening plants used cationic polymer as filter aids. The results of pilot studies of the filtration of alum-coagulated waters indicated that at high filtration rates, by using appropriate polymer as filter aid, effluent turbidity and microbial removal can be maintained as experienced at low filtration rates (Robeck et al. 1964, Conley and Hsiung, 1969) .

The mechanisms of polymer-particle interactions are similar to the coagulants used in the coagulation-flocculation process. Overall rate of coagulation-flocculation within filters is determined by multiplying the general coagulation-flocculation rate by a collision efficiency factor which reflects the ability of chemical coagulants to destabilize colloidal particles and thereby permit attachment to the collectors when contacted. Polymer-particle interactions can be described by charge neutralization, where particle destabilization is attained by the adsorption of opposite-charged polymers on particle surfaces, and inter-particle bridging where a cross-linking structure of polymer and particles are formed. Another mechanism identified in the literature is the charge neutralization/precipitation model (Edzwald, 1983) which is expected with the use of cationic polymers when humic substances are present in the influent. Aggregates are formed from a cross-linking between the negatively charged humic macromolecules and cationic polymers.

Improvement of attachment efficiency by using proper type and optimum dosage of coagulants such as alum or polymer, etc., is a key aspect to improve particle capture efficiency. It should also be kept in mind that increasing particle capture efficiency may clog the top portion of the filter bed and lead to rapid headloss development. Pilot studies are required to establish optimum coagulant use as filter aid to suit individual plant conditions.

1.2.3 Effluent Control Methods in Filtration

Constant rate filtration as applied to rapid filtration was first introduced in the 1890's. The effluent control methods differ primarily in the way the driving force is controlled across the filter. Constant rate filtration can be divided into three types: i) constant flow (Figure 1.3a); ii) constant water level (Figure 1.3b), and; iii) influent flow splitting. The filtration rate is controlled individually by an effluent rate control valve. In constant flow filters, each control valve is operated automatically to regulate the amount of flow through the filter.

Constant level filters contain a valve in each filter effluent pipe to maintain constant water level by adjusting the flow (Figure 1.3a). Constant level filters are useful when the plant layout is restricted by the topography in which water level changes in the filters may seriously affect the plant hydraulics and hence the treatment plant operations. Constant level operations are achieved with the help of level sensors and flow modulating valves (Figure 1.3b). The influent flow splitting system contains an influent weir at the entrance of filters which splits the total plant flow equally to all the filters. Such system does not have any effluent flow controllers. Though, water level in individual filters changes, the total plant production will remain constant (Cornwall et al. 1991).

The alternative control method, declining rate (Figure 1.3c), became established in the 1950's (Hilmoe and Cleasby, 1986). Declining rate filtration is the condition where no attempt is made to keep flow rate constant, throughout the filter cycle. A flow restrictor, generally an orifice plate, effluent weir, valve or a combination of those, was used to preset the initial flowrate through the filter. It should be noted that no attempt is made to modulate the flow by the restrictor during filter operations. It has been reported (Arboleda-Valencia et al. 1985) that in Latin America more than 100 treatment plants were either designed with declining rate filters, or the existing constant rate filters had been converted to declining rate mode. Monk (1987) presented the advantages, hydraulic controls and variations applicable to declining rate filtration. A full scale study indicated that 40 percent more water is produced by converting constant rate filters to declining rate (LaRoche, 1989).

Cleasby (1969) proposed the variable declining rate operation, in which the filters communicate through the common influent channel and the effluent weir. All filters will have the same headloss which varies during filter operation. Such system can be divided into two main categories: i) influent controlled, and; ii) effluent controlled. Effluent control is achieved by the effluent restrictor. Similar flow restrictor is employed in the influent channel for influent control method. Cleasby (1969; 1981) described systems with effluent flow restrictors and Arboleda (1974) reported declining rate systems with flow restrictors in the individual influent pipes.

Arboleda-Valencia et al. (1985) discussed the continuous declining rate filtration scheme where water level and the total headloss are kept constant. However, this control method cannot be implemented because there are always flow variations and the filtration rates change with time during the run, especially, when a filter unit is taken out of service for backwashing. Closest approach to the above concept was previously developed by Hudson (1963). This utilized an outlet manifold to connect the filters and transfer the filtrate to an equalization chamber.

Another effluent control scheme that has been later developed is the equal-loading self-backwash filtration (Figure 1.3d). This is expected to have low energy requirements, simplicity of operation and eliminates the need for backwashing appurtenances (Montgomery, 1985). Among the effluent control systems, declining rate systems have many advantages over the constant rate control such as better effluent quality, longer filter runs or more water production, better resistance to flow increases and less detrimental to effluent quality (Cleasby and DiBernardo, 1980).

1.2.4 Filter Media Aspects

Selection of the proper filter media is an important aspect of the design of plants that utilize coagulation and filtration. Performance of a granular filter media is determined by the size of the media, the shape of the media (whether angular or rounded), the gradation in size of a layer of media, the depth of each layer, the total depth of media, the degree of intermixing of layers of different sizes and density of media (for multi-media filters only). All these variables impact upon the operation of the filter. In addition to the filtrate quality and headloss development in the filters, the choice of filter media affects the backwashing characteristics as well. The operating characteristics of a media are generally discussed in terms of effluent turbidity and headloss which determines the length of filter operation before it requires cleaning, and the net unit water production (Bishop, 1981).

Many types of filters are used in water filtration. Based on the media type, the filters can be classified as mono-media sand, dual-media with anthracite, and precoat filters. Quartz sand, anthracite, garnet and occasionally, granular activated carbon are the commonly used filter media in water filtration. Anthracite is used in dual-media filters with other materials. The mono-media filters are gradually replaced by the dual-media filters in modern treatment plants, thereby giving the advantage of coarser anthracite media. This promotes improved interstitial flow that gives extended filter runs. Advantages of dual-media filters were summarized in Robeck et al. (1964).

Traditionally, most of the filter media is obtained from the natural environment and sieved to give the required size distribution to be used in filtration. By improving the particle capture characteristics, the performance of filter media may be improved. This can be achieved by using various shapes of media such as, crushed (sharp edges facilitate charge concentrations) and rounded. Quartz sand is commonly used as filter media. Quartz has a highly stable crystal structure. No weakly bonded ions are available in quartz to create surface charges (Mitchell, 1976). However, during the crushing process, its crystal structure can be broken to increase surface charges.

Coating the filter media in order to improve particle capture efficiency was investigated in the 1970's. Oulman and Baumann (1971) evaluated many coating materials and showed that by coating the filter media, it was possible to reverse its surface charge (zeta potential) from negative to positive. This improved the adsorptive ability of the media since nearly all natural suspended solids in surface waters are negatively charged in the neutral pH range (Baumann and Oulman, 1970). Later, Byeseda and Sylvester (1979) investigated the performance of polymer precoated filter bed and found that filter runs were extended by nearly an order of magnitude. Polymer coated diatomite material was studied by Burns et al. (1970). Though coated media effectively improve filter performance, there are some concerns regarding the abrasion of coatings during backwash, thus requiring re-coating of the media. The expenses of coating process impose economical restrictions on the viability of coated media in filtration. Coating of filter media was not investigated in this research.

1.2.5 Initial Degradation of Effluent Quality

Progressive clogging of filter pores with time and depth will change the filtering characteristics of the granular material due to locally altered geometry and hydrodynamic conditions of filter pores. This will ultimately lead to a deterioration of filtrate quality, and filtration must be stopped. The accumulated retained particles which are deposited in the filter pores must be removed. Such removals are normally achieved by washing upwards with clean water. This fluidizes the filter bed, freeing the deposits which are then washed away. This backwashing may be accompanied by auxiliary surface wash or air scour. A number of alternative backwashing systems which are currently used are discussed in Cleasby et al. (1975; 1977).

Operators of municipal water treatment plants have long recognized a brief period of increased effluent turbidity immediately following backwashing of a filter. Research has indicated that the period of initial effluent degradation is a function of the remnant water remaining in the filter at the end of backwash (Amirtharajah and Wetstein, 1980) and/or a function of influent (Francois and Van Haute, 1985). The subsequent period of effluent quality improvement, or the filter ripening has been related to the accumulation of influent particles within the pores of filter media, resulting in increased capture of further particles (O'Melia, 1985; Payatakes et al. 1981). Further research has been conducted to determine the association of increased transport of potentially pathogenic microorganisms through the filters, with the initial period of effluent quality degradation (Logsdon et al. 1985). The initial period of effluent quality degradation and the subsequent improvement has been termed as the filter ripening sequence in current literature.

A number of studies have been reported in the literature investigating the improvement of water quality and the reduction of water wasting during the filter ripening sequence. One of the methods considered have been the addition of coagulants to the backwash water and implementing a 'filter-to-waste' procedure where after backwash, the filtered water was wasted until required effluent quality is achieved by the filters. The addition of coagulant to the backwash water has been suggested as a mean of preconditioning the filter by adsorption of the added coagulant to the filter media (Harris, 1970; Yapajakis, 1982). The use of filter-to-waste period at the beginning of the filter run can also be effective in reducing the initial period of poor quality product water.

However, due to the significant length of the filter ripening sequence, this procedure may induce excessive consumption of raw water and energy.

Unless the effluent turbidity is brought to a value below a limit where the probability of microbial contamination is reduced to an acceptable level, the risk of microbial contamination of drinking water will exist. Even with the use of coagulants, a mandatory filter-to-waste procedure at the beginning of the filter run is required to eliminate microbial contamination of filtered water (Logsdon et al. 1985). Therefore, optimization of the operating parameters such as filtration rate, influent turbidity and others, which could possibly influence filter ripening, is very important for minimizing the filter-to-waste period. This can lead to substantial savings in energy and operating costs while producing filtered water free from the risk of microbial contamination.

1.2.6 Monitoring Filter Performance

In studies to improve filter performance, appropriate monitoring parameters need to be identified. Filtrate quality is the key factor in filtration monitoring. Turbidity is the main indicator of water quality used in water treatment for many decades. Particle counts of filtered water rapidly gained acceptance as a tool for monitoring water treatment processes due to the interest in microbial characteristics and the suspicion of microbial quality representation by turbidity measurement (Hargesheimer et al. 1992). Compared with the other methods of monitoring water clarity, particle count provides more information with greater sensitivity because particles are individually sized and enumerated. These attributes are useful when the traditional turbidity measurement is at its lower limits or it is not providing adequate discrimination between water samples. Though site and process specific, there exists a correlation between turbidity and particle count measurements (Le Chevallier and Norton, 1992; McCoy and Olson, 1986). Lewis and Manz (1991) conducted studies in particle counts of filtrate quality and found that particle counts and turbidity yielded useful information for turbidities greater than 0.2 NTU.

An advantage of turbidity measurement over particle counting is that the turbidimeters can detect sub-micron size particles, which most particle counters except expensive, sophisticated ones, cannot measure. At low turbidity, the poor sensitivity of turbidimeter at low particle concentrations makes particle counting advantageous (Letterman, 1994). For efficient assessment of filtration performance, continuous turbidity monitoring, particle counters and monitoring of microbial parameters are essential (Bellamy et al. 1993; Miller, 1994).

Another operational parameter of filter performance is the headloss development across the filters which is an indirect indication of the clogging of filters due to accumulation of deposits in the pores of the filter bed. The development of headloss within the filter media depends on the rate of particle removal, filtration rates and the geometry of the interstitial spaces within the filter bed. Any increase in filtration rate and influent turbidity tend to increase the headloss. Many mathematical models to describe the headloss across filters were summarized in Metcalf and Eddy (1991). As the headloss increases, the flow passage through the filter media will be reduced which results in lower filtration rates. As the headloss increases, the water level in the filters also will increase depending on the type of filter effluent control scheme. After a specified headloss is reached, filtration must be stopped for backwashing. Therefore, headloss also governs the length of a filter run. Once the filter run length is defined by headloss, or turbidity breakthrough, the water production during a filter run can be calculated.

1.2.7 Filtration Pilot Plant Studies

Pilot plant studies are necessary and helpful in view of many issues such as comparing effectiveness of alternative processes, ascertaining the cause of undesirable effects, establishing design criteria, estimating operating costs, discovering unforeseen treatment problems, investigating treatment modifications, establishing confidence in proposed treatment methods and providing information on the effectiveness of a treatment process to regulatory authorities (Thompson, 1982). Increasing costs of construction and operation led the designers to conduct pilot plant studies, limiting the scope of such studies to those essential aspects of particular processes. Therefore, conducting a pilot plant study to develop information on alternative filter media and operating protocols for the Rossdale water treatment plant was very appropriate. A discussion of the application of filtration theory to pilot plant design is available in Adin et al. (1979).

Validity of pilot plant data and their limitations needed to be examined before implementation. Studies had shown that the pilot filter data from carefully conducted and controlled works were sufficiently representative of full size plants that they provided a direct basis for design. This has been established time after time by experience in the water industry (Hudson, 1982). Ives (1966) and Davis (1983) conducted studies and concluded that there did not exist a scale-up factor for filtration models and pilot plant performance. Therefore, the feasibility of scale-up factors for the pilot plant study parameters needed to be considered. The effluent turbidity, headloss associated with filter bed clogging, effects of media type, size and shapes could be studied in a pilot plant. Identical geometric similarity between the pilot and full scale filters eliminate the need for scale-up factors. No significant difference in the pilot and full scale filter results was expected if the diameter ratio of filter bed/filter media is greater than 25 (Davis, 1983). A limitation of pilot plant studies was the absence of lateral flow within the filter bed and related properties that exist in the full scale filters. The impact of the above on turbidity removal was not expected to be significant. However, inferences about filter backwash should not be made in small columns due to the reason that such columns would not accommodate the violent turbulence and the boiling of media surface, a predominant occurrence in full scale filter backwash.

Another matter of concern with modeling studies conducted in small pilot columns was the drawing of samples from time to time through sample ports during filter operation. When the flow hydraulics within the media was altered due to sampling, reorientation of filter media may occur, thus affecting the filter performance. This was probably a prime reason for the lack of representation of actual filter performance by the mathematical models which were developed from small pilot filter columns. In many pilot plant studies, 150mm diameter columns were used to minimize the wall effects on filter performance. This size of column was shown to produce acceptable results in terms of turbidity removal associated issues.

1.3 Research Objectives

The primary hypothesis of this thesis was that filter media and operating protocols affect the efficiency of particle removal in rapid sand filters. The boundary condition of the pre-filtration treatment processes used on the North Saskatchewan River water by the Rossdale water treatment plant prevailed for this study. With this as the overall hypothesis, the main objective of this research was to upgrade filtration process to produce water that has lower turbidity values then required by the Canadian and U.S. effluent turbidity standards. The specific objectives are:

1. To improve filter performance to meet and to better the progressively stringent quality standards by:
   - a. selecting a filter media which can provide better effluent quality; and
   - b. establishing optimum filter operating conditions.
2. To formulate a rational filter design procedure based on effluent turbidity to predict long term filter performance from pilot plant results. This design procedure will be used to check for compliance with the more stringent standards.
3. To establish optimum filter ripening conditions to reduce the risk of microbial contamination and to conserve energy.

1.4 Scope of the Study

From previous filtration research, effluent quality improvement can be achieved by: i) choosing proper filter media; ii) using coagulant as filter aid; iii) selecting appropriate operating conditions for filtration rate and influent turbidity by controlling pretreatment processes; iv) controlling the temperature; and v) providing appropriate effluent control methods. Due to the nature of many factors influencing filtration, lack of representation by existing mathematical models, and variations in the influent quality and treatment objectives, conducting a pilot plant study to evaluate local needs, those of Rossdale water treatment plant in this study, was found to be appropriate. Due to the complexity of many parameters affecting filtration, the pilot plant study was conducted in phases.

Screening experiments were performed on different filter media types. The effects of filtration rates on filter media, which were chosen from screening experiments, were studied (Chapter 2). Based on the results of the screening experiments, selected media types were further compared by studying their physical properties, especially, abrasion resistance and the effects of polymer addition (Chapter 3). The filter media performance during 'shock' situations, where a hydraulic surge is experienced in the filters, were also compared (Chapter 2 and 3).

Filtration data were analyzed in a statistical manner and a rational design procedure based on the reliability of filtration was formulated (Chapter 4). This design procedure was used to predict long term filter performance using the pilot plant data and to check the compliance with the Canadian and U.S. effluent turbidity standards. Optimum filter ripening conditions were established for economical filter operations, which would eliminate or minimize the risk of microbiological contamination of drinking water (Chapter 5).

The results of the study provide more understanding about the principles of optimization of filtration using pilot plant studies. The use of statistical concepts in the analysis of pilot plant data was important to compensate for the uncertainties and variations expected in pilot plant operations. The existing filtration plants have benefited from the use of the study findings by providing a better water quality which betters the more stringent effluent standards.

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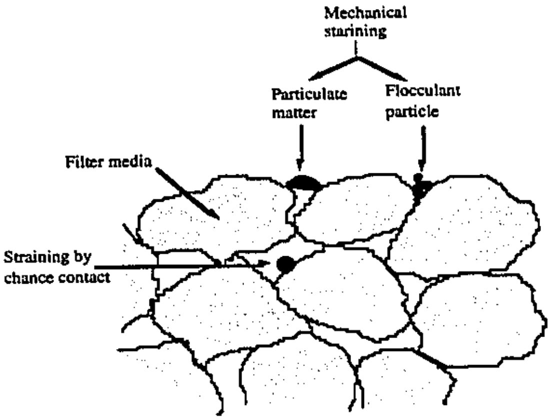

Figure 1.1 Particle Removal By Straining Mechanism (after Metcalf and Eddy, 1991)

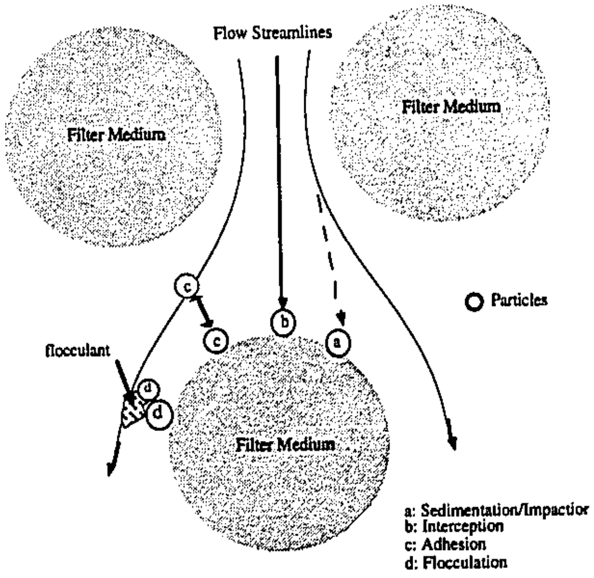

Figure 1.2 Particle Removal Mechanisms Within A Filter (after Metcalf and Eddy, 1991)

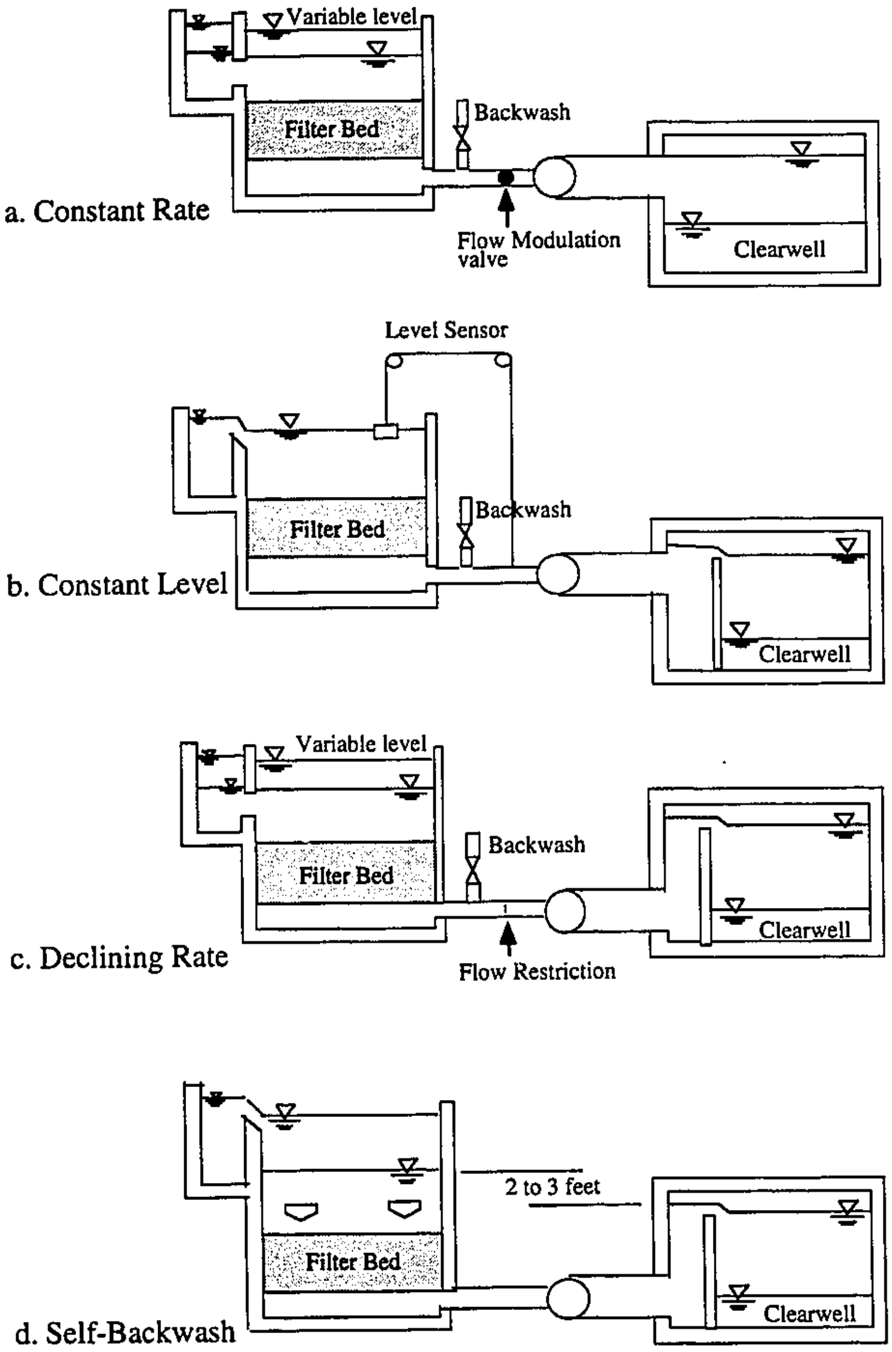

Figure 1.3 Basic Types of Filter Control Systems (after Montgomery, 1985)

Chapter 2

Filtrate Turbidity Improvement of Existing Mono-Media Filters Based on a Pilot Plant Study

2.1 Introduction

Water treatment plants use various types of filter media such as conventional sand, anthracite, garnet, and illmanite. The filters may consist a mono-media, dual-media or multi-media. The most commonly used filters generally consist of conventional sand either as mono-media or with anthracite as dual-media (Cleasby, 1990). Filters at the Rossdale water treatment plant in Edmonton, Alberta contain conventional mono-media filter sand and are currently operated at constant rate.

Effluent turbidity data collected from the filters at Rossdale water treatment plant indicate the water would violate the new licensing requirements of the Province of Alberta and the in-plant turbidity objectives. Effluent quality could generally be improved by improving the filter performance, the pretreatment process or both. Numerous in-plant studies on the pretreatment process under different seasonal raw water had been conducted previously. Although further improvement is always possible, current operation can be considered to be near optimum pretreatment conditions. Therefore, the filters need to be upgraded using a better filter media in terms of effluent turbidity to meet the turbidity goals while providing excellent water production.

In addition to meeting the effluent turbidity goals, some important operating characteristics such as filter ripening and the criteria to determine the termination of a filter run are also needed to be considered in upgrading filters. When a filter is put into service

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after backwashing without using ripening techniques, initial degradation of effluent quality and subsequent improvement occurs. This is referred to as the filter ripening sequence (FRS) (Amirtharajah and Wetstein, 1980; Amirtharajah, 1985: Francois and Van Haute, 1985). The new media should have ripening characteristics such that the initial effluent quality degradation is minimal and short.

Filter run termination (Figure 2.1) is generally defined either by allowable headloss across the filter bed (h_L) or when the effluent turbidity reaches a maximum allowable value (T_L). However, many full scale filtration plants also adopt a maximum time criterion (t_L) to avoid microbial growth and excessive accumulation of influent particles within the pores of filter bed. This may require extensive filter backwashing or may cause mudball formation (Cleasby, 1990). Maximum time of filter operation varies from 24 h to 120 h depending on plant operating conditions and legislation (Cleasby et al. 1989). Saturation of the filter bed with influent particles may pose a threat as it may cause effluent turbidity spikes during small flow variations.

In addition to the above factors, some constraints had to be considered in the filter upgrade. The available head for filter operations was limited by the existing plant hydraulics. The location of the underdrain system and influent weirs was limited by the existing filter construction. During backwash, the selected media expansion was limited by the existing weir level to prevent media loss. As a result, pilot scale tests were designed to recognize these constraints.

While some unit processes in water treatment are difficult to scale-up from pilot studies, filtration has been recognized in the literature as an easy water treatment unit process to scale-up (Davis, 1983). As a result, it was concluded that the results from the pilot plant should be valid at full-scale. However, in pilot scale evaluations, there is always concern about the relationship between performance at the pilot and full scale, as there is never complete agreement between pilot and full scale operation. A pilot plant was built to simulate the physical and operating conditions of the full scale filters to choose a better filter media based on a comparative study. In general, many aspects of filtration, such as media type, grain size, bed depth, etc., can be learned from pilot filter columns. Due to the restrictions on the existing filter and backwashing facility design, the optimizations of media size and filter bed depth were not conducted in this study.

This paper describes a comparative study to select new filter media for the Rossdale Water Treatment Plant in Edmonton, Alberta. Pilot scale filter tests were performed to select a media which would meet stricter turbidity guidelines under the normal physical and treatment conditions. Filter media was selected based on effluent quality, headloss criterion and the physical constraints posed by the existing filters. As guidelines were based on statistical concepts, filter performance was analyzed statistically. This study was conducted in two phases. Phase I involved in screening experiments conducted under all seasonal influent conditions. Phase II was designed to study the effects of filtration rates on a comparative basis.

2.1.1 Treatment Process at The Rossdale Water Treatment Plant

The major process train of the Rossdale water treatment plant consists of coagulation, flocculation, sedimentation, softening, filtration and disinfection. Raw water is obtained from the North Saskatchewan River and is heated during cold weather. Chlorine dioxide, powdered activated carbon (seasonal), ammonia and alum are added in a rapid mix zone, followed by flocculation and sedimentation. The clarifiers contain inclined tube settlers. Softening is achieved in another similar clarifier after lime addition. The recarbonated clarifier effluent is conveyed to filters through a stilling basin, with chlorine and fluoride addition. The plant has nine filters with a total area of 1620 m^2. Filtration rate at the plant capacity is 7.3 m/h. At present, the filters contain silica sand (effective size, ES = 0.61 mm; uniformity coefficient, UC = 1.34) and are operated in a constant rate control method. The filter depth from the gullet floor to the maximum water level was 3.1 m. Any physical modification (weir level, media depth, media expansion during backwash, underdrain system) to the filter is restricted to fit to this depth. The filters are constructed indoors and the filter influent temperature is generally 3 to 6 degrees warmer than the raw water, especially during cold weather.

2.1.2 Effluent Turbidity Standards

Turbidity in water is caused by the presence of suspended matter. Some types of material which cause turbidity can serve as a source of nutrients for microorganisms. The most important health effect of turbidity is its interference with disinfection and the maintenance of a chlorine residual. The amount of turbidity in the finished water can be related to the effectiveness of the treatment process in the removal of microorganisms. The recent availability of highly sensitive instruments and a better understanding of turbidity and associated parameters have generated increasingly stringent turbidity standards for potable water. This shows a necessity of improving the performance of water treatment plant, especially filtration, to meet the more stringent guidelines.

2.1.2.1 Federal Guidelines

The Guidelines for Canadian Drinking Water Quality (Eco/Log, 1993) recommend a maximum acceptable turbidity of 1 Nephelometric Turbidity Unit (NTU) for water entering a distribution system (5 NTU may be permitted if it can be demonstrated that the disinfection is not compromised by the use of this value). The frequency of sampling is not specified. However, it is stated that the effluent turbidity should be less than 1 NTU for 95 percent of the operating time of an individual filter.

2.1.2.2 Province of Alberta

The Government of Alberta generally adopts the latest edition of federal drinking water quality guidelines. However, the interpretation, monitoring and regulations are defined in the water treatment plant licence to operate requirements by the provincial government. Until April 1993, the Licence to Operate requirements for water treatment plants in Edmonton, Alberta was the following: (i) Individual filter turbidity to be less than 1 NTU 95% of the time and never exceeding 5 NTU and (ii) Combined filter turbidity not to exceed 1 NTU for more than two days per month and never to exceed 2 NTU. The 1993 amendment to the Licence to Operate is: (i) individual filter turbidity to be less than 1 NTU, 99% of the operating time and never exceeding 2 NTU; and (ii) daily arithmetic average of combined filter turbidity not to exceed 1 NTU.

2.1.2.3 Other Provinces

All other provinces in Canada adopt the federal guidelines, however, the interpretation differs slightly. As of April 1992, the province of Quebec required finished water turbidity of less than 1 NTU for drinking purposes and 5 NTU for non-drinking purposes. At the time of this study, the province of Manitoba encouraged water treatment plant operators to comply with the 1 NTU standard all the time. The province of Ontario follows the federal guidelines (personal communication, 1994). The province of Saskatchewan also adopted the federal guidelines but the requirements have to be met approximately 90 percent of operating time in a calendar month (personal communication, 1993).

2.1.2.4 Rossdale Water Treatment Plant Turbidity Goals

While satisfying the federal water quality guidelines and the provincial licensing requirements, Rossdale water treatment plant has established an effluent turbidity limit of 0.1 NTU during normal filter operations. End of filter ripening is determined when the turbidity of the cleaned filter reaches 0.2 NTU.

The trend in provincial interpretation of the federal water quality guidelines suggests that the drinking water quality requirements are becoming more stringent. Water treatment plants will have to produce water of quality better than the requirements by upgrading their performance.

2.2 Need For Study

Operating data for the existing full scale filters were analyzed for the period of March 1991 to August 1991 for possible violations of the 1993 licensing requirements. Table 2.1 indicates the need to upgrade filters at the Rossdale water treatment plant. Some of the violations may be caused by the influent turbidity spikes, carry-over of added chemicals such as alum, lime, and excessive air binding during the period when raw water was heated. Possible alternatives, that were considered in this study to improve filter performance, included the use of a better type of filter media which can withstand influent turbidity spikes and which are tolerant to sudden flow changes or shocks. A pilot scale filter study was conducted as part of the investigation for the upgrading of filters at the Rossdale water treatment plant. Phase I of this study involved the design and construction of the pilot plant along with screening tests on a number of different types of media. Based on the result and recommendations of the first phase of study, Phase II of the study was designed. This involved further tests on the performance of two types of media at different filtration rates.

2.3 Filtration Pilot Plant

The pilot plant was built in the Rossdale water treatment plant, to match the bed depth and weir elevations of full scale filters. Details of the pilot plant are shown in Figure 2.2. Six clear PVC tubes of 150 mm diameter were used as pilot filter columns. Due to restricted headroom in the selected location for the pilot plant, a closed-top construction had to be employed. Full scale filter influent (coagulated, lime-softened and clarified) was drawn from the feed water channel and was split through a header to all six columns. Constant rate control downstream of the columns was achieved by a constant level (float controlled) header tank, as suggested by DiBernardo and Cleasby (1980). It provided a constant head on a throttling, manual needle valve. The float valve on the constant head tank modulates to compensate for the headloss caused by filter clogging. The filtration rate was set by reference to the rotameter and was checked periodically with a stop watch and graduated container. Headloss measurements were obtained by the difference in water levels of the piezometer tubes located at the top and bottom of the filter bed, which was recorded every two hours by a remote camera. Filtered water turbidity was measured every 5 minutes by 'flow-through' low range turbidimeters (Hach® model no. 1720C) which are similar to those installed in the full scale filters. The 4 to 20 mA outputs from the turbidimeters were recorded by a datalogger, from which the data could be downloaded to a computer. The turbidimeters were calibrated every month by checking meter readings with laboratory measurements of turbidity. The turbidimeters were in very good calibration throughout the test period (coefficient of variation of 3.5%). A polymer feed system was installed with a multi-tube peristaltic pump. As required, polymer was injected into the feed pipes to the column, against the flow.

2.3.1 Compensation for Influent Quality Variations

In this pilot plant experiments, the influent quality could not be controlled since the pilot plant influent was the same as the full scale filter influent. The operating criteria of the pretreatment units of the full scale plant (coagulation, flocculation, clarification and softening) were determined by the operator according to the raw water conditions. Depending on the degree of softening and recarbonation, the water entering the filtration pilot plant may either have: (i) a scale forming potential which triggers post-precipitation of calcium carbonate in the pores of the filter bed and causes additional headloss; or (ii) corrosive potential which tends to dissolve precipitates (Montgomery, 1985). In addition, during plant upsets, there can be a carry over of excess chemicals, which eventually must be captured in the filter bed. To compensate for the lack of influent quality control when using plant water for the pilot plant, each experimental condition must be operated for a reasonably long period. This includes a sufficient number of filtration cycles to obtain a good representation of filter performance. The use of actual plant filter influent assures that the evaluation of filter media performance is based on actual conditions found in the full scale filters when the study is conducted during all seasons. Effects of seasonal variation of the water quality and plant operations can be investigated by analyzing the data collected during different seasons.

2.4 Phase I of the Study: Screening Experiments

2.4.1 Experimental Procedure

The primary objective of Phase I of the study was to screen a number of media types to determine which ones may be able to meet the 1993 guidelines. During Phase I of this study, the filtration rate through all filter columns was held constant at 7 m/h, a rate subjectively selected as typical full scale rate at the plant capacity. Table 2.2 describes the media configuration of pilot columns. Existing filter media was employed in one filter column as a control. During the first month of operation, sand/garnet dual-media (F6) experienced very high headloss. In addition, extensive intermixing along the filter bed was seen after backwashing. As a result, this media was abandoned. It was also found that column F1 was not representative of the full scale media because of the method it was obtained from the existing filters. To obtain representative media from the full scale filters, it was found that numerous small cores from different depths and locations in the full scale filters were necessary. Full scale filter media was replaced in column F6 in April 1991. This column was found to better represent the performance of the full scale filter.

2.4.2 Polymer Addition

Limited polymer addition studies were also conducted in the first phase of the study. PERCOL® LT20, a high-molecular weight, non-ionic polymer, available in powder form was used as filter aid. Stock solutions of the polymer (5000 mg/L) were prepared once a week to prevent aging and were diluted to working solutions on a daily basis. A peristaltic pump with four different feeders was used to feed the polymer to pilot columns. The amount of polymer fed to the filters was monitored daily and checked with the intended polymer dose (coefficient of variation of 5.3%). Feeders were interchanged between trials to minimize the errors in feed rates in different feeders. A survey of some filtration plants (Cleasby et al. 1989) indicates applied polymer doses of up to 0.08 mg/L as filter aid. Average polymer dose in this study was 0.01, 0.025 and 0.01 mg/L for the columns F3, F5 and the original F6 (sand/garnet only), respectively.

The average filter influent turbidity during the first phase of the study was 3.9 NTU with a standard deviation (stdev) of 1.13 NTU. During the period of March/April 1991, the water temperature was less than 5°C. During May to July 1991, the temperatures were warmer (13 to 18°C).

2.5 Phase I Results and Discussion

2.5.1 Effluent Turbidity

A total of 23,000 turbidity values for each column was analyzed. The turbidity data were grouped and the summary of the mean and the standard deviations were first reviewed to understand which type of filter performed better (Table 2.3). While some tendencies were observed from average turbidity results, the differences were very small. Further inspection of the data revealed that some of the filters tended to perform more consistently than the others. Table 2.3 suggests that the average turbidity of all filter types were not significantly different. Therefore, a comparison based on the average turbidity may not provide the required information on performance. Standard deviation of the turbidity data suggests that the columns F4 (crushed quartz) and F5 (dual-media with polymer addition) were less than half of the values of F2 and F3 (Table 2.3). It may be concluded from this analysis that crushed quartz (F4) or the dual-media (sand/anthracite) filter with polymer addition (F5) performed more consistently than the other filter types (at a significance level [α] of 0.001). Filtrate turbidity data during April to June 1991 were compared to the 1993 licensing requirements. Only the filter columns F2 and F3 had produced effluent turbidities exceeding 1 NTU, however, the frequency of occurrences did not constitute violations.

2.5.2 Headloss

A limiting headloss of 1 m was adopted to determine the run termination which was also used for the full scale filter operations at Rossdale water treatment plant. The above criterion is restricted to 1 m by the maximum available head in the full scale filters. For comparison purposes, the filter run length (FRL) of all filters for 1 m headloss was studied. Clean bed headloss (CBHL) was also recorded for each filter cycle. It characterizes the initial porosity of the filter bed and as a result, was used to check for consistency of backwash. Table 2.4 provides a clear indication of the effect of water temperature on filter headloss. Cold weather operations resulted in 50 to 60 percent reduction in FRL and similar increase of CBHL compared to that of warm weather operations. This is mostly attributed to the change in viscosity with temperature because adequate backwashing was provided for all experiments. Higher viscosity at lower temperatures increases CBHL (Carman-Kozeny Equation, Montgomery, 1985). Increased CBHL at reduce the available headloss for filtration thus reducing FRL at lower temperatures. Filtrate turbidities were also found to be reduced by approximately 50 percent with temperature increase. Viscosity changes affect particle capture mechanisms in filtration. At higher temperature, due to lower viscosity: i) particle capture by sedimentation is increased due to the increase in settling velocity; ii) perikinetic (Brownian) flocculation of particles is increased due to the increase in collision efficiency; and, iii) the drag forces of the particle is reduced (Montgomery, 1985). Particle detachment is also reduced at higher temperatures due to reduction in fluid shear (Montgomery, 1985). Such effects on particle capture mechanisms improve particle capture at higher temperatures. Higher CBHL observed for F2 and F3 is an indication of the reduced initial porosity of the filter bed. However, it does not necessarily mean that better quality filtrate is produced as this involves several mechanisms of particle capture in the filter bed (Tchobanoglous and

Eliassen, 1970). FRL results indicated that only the crushed quartz and sand/anthracite dual-media operated similar to the full scale filters.

2.5.3 Shock Tests

When a filter taken out of service for backwash or maintenance, a flow surge is experienced by the other filters, especially, in treatment plants with small number of filters. Changes in plant operational strategy may require a flow increase in the filters. Therefore, shock loading tests were conducted by increasing the filtration rate from 7 m/h to 13 m/h over a 2 to 3 minute period, after 24 hours of filter service time. The results are summarized in Table 2.5. Shock resistance of the existing media was poorly indicated by large filtrate turbidity spikes. Crushed quartz and dual-media with polymer addition performed much better than the mono-media rounded sand.

Comparison of the above factors seemed to indicate that the crushed quartz mono-media filter and the dual-media (sand /anthracite) filter with polymer addition could possibly be used to replace the existing filter media to meet the more stringent standards. Further experimentation was required to discriminate among those filter types to determine which had superior performance.

2.6 Phase II of the Study: Performance Comparison

Phase I of the study was conducted at a single filtration rate for long term performance comparisons. Phase II was designed to study flow effects on the performance of crushed quartz, dual-media (sand/anthracite) filters and existing media as control. The filter configurations can be found in Table 2.6.

Ideally, a factorial designed experiment (Box et al. 1978, Davies, 1954) would be the best approach to study the effects of all major parameters that influence filter performance. However, limitations in time and equipment did not facilitate a complete factorial experimental design to optimize the filtration performance. Lack of control on the influent quality (which may change during the study period) would also hamper the factorial experimental design for process optimization. It was possible, however, to develop an experimental procedure based on factorial design principles which may be used to study some effects for the purpose of comparing alternatives. The order of the experiments was randomized to distribute the experimental errors over all the filters. Even though randomization prevents some side-by-side comparison, it is advantageous since it spreads the errors caused by variation of influent quality and unavoidable operational errors evenly over the study period. To ensure that data are representative of the actual performance, numerous filter runs were completed at each operating condition. The number of runs varied from a low of 6 to a high of 21 for the various operating conditions. Termination of a filter run was determined by: (i) filtrate turbidity exceeds 1 NTU (except for turbidity spikes) or (ii) the headloss across the filter media exceeds 1 m. The maximum time limit of 60 hours, which is imposed on the full scale filters, was not adopted in the pilot plant because of the purpose of comparing different filter media by its FRL.

2.6.1 Filtration Rates

Filtration rates used in the Phase II were 12.5, 8 and 3.5 m/hr. The high filtration rate of 12.5 m/hr was selected to represent a worst case scenario if more than one filter had to be down or the plant was forced to increase its production. The low filtration rate represents the low capacity flow. In addition, these settings allow the study of effects of filtration rates on filter performance based on the factorial experimental design concepts. The filtration rate of 8 m/h that corresponded to plant capacity was also studied.

2.6.2 Influent Turbidity and Temperature

The average influent turbidity for the phase II was 10.5 NTU with a standard deviation of 2.1 NTU and a range from 1.4 to 29 NTU. The average is somewhat higher than monthly averages for the same months in 1990. Water temperature throughout the study was relatively constant (4.5°C ± 0.5) as the raw water was heated during the study period. However, this temperature is quite different from what would be expected during summer operation. As a result, care should be taken in generalizing these results to year-round operation. However, it should be noted that the cold water temperatures present during the second phase of the study represent the more difficult filtration conditions. This did not adversely influence the comparative nature of this study.

2.7 Phase II Results and Discussion

Table 2.6 summarizes the results obtained from the study. Included in this table are the filtration rate, influent and range of average filtrate turbidities, CBHL, FRL and water production capacity (WPC) which is the volume of water produced during one filter cycle. The end of filter ripening was determined either as the end of receding limb (Amirtharajah and Wetstein, 1980) if the effluent turbidity is less than 0.2 NTU or the time taken to reach 0.2 NTU effluent turbidity. Generally, it occurred within 5 to 15 minutes after backwash.

The shape of a probability plot (Figure 2.3) of effluent turbidity may indicate some trends in filter performance. A straight line of the normal probability plot would indicate that the effluent turbidity is normally distributed (Kennedy and Neville, 1976). However, the observed effluent turbidity data were not normally distributed. This is also evident by the skewness of the distribution (Table 2.6). Deviations from normality are also noted in the effluent turbidity histograms (Figure 2.4). This suggests that the traditional statistical analysis such as comparison of average turbidity of filter runs and calculation of standard deviation that has been used in analysis of filtration performance is of concern as typically it is assumed that the observations are normally distributed and to have constant variance. Results based on such analysis may lead to misinterpretation of the filtrate turbidity data. This can be avoided by transforming the effluent turbidity data to make them normally distributed. This will be discussed later in the factorial experimental analysis.

Probability plots (Figure 2.3) may be used to check the compliance of the filter operation with the turbidity standards. These require effluent turbidity to be less than the limiting turbidity for a specified percentage of operating time. The plots show that the turbidity of all three filter types investigated never violated the 1993 licence requirement during the operating cycles. The use of dual-media and existing filter sand at a filtration rate of 12.5 m/h may be of concern as the turbidity for 99% operating time is in the vicinity of 0.85, which is close to 1 NTU. However, it should be noted that 12.5 m/h is seldom or never experienced by the full scale filters at Rossdale water treatment plant especially under cold water temperatures.

2.7.1 Average Turbidity

Figure 2.5 shows the variation of average effluent turbidity of individual filter cycles and its range of variation with filtration rates. Existing filter media and crushed quartz had the lowest turbidity values at 3.5 m/h filtration rate while the dual-media had higher average turbidity. At 12.5 m/h, all the average turbidities were higher. It is of interest to note that both the crushed quartz and dual-media experienced lower average turbidities at 8 m/h than at 3.5 m/h. One possible explanation for this phenomenon may be the existence of a filtration rate (8 m/h, in this study) compromising between shear detachment and orthokinetic flocculation within the media. Moran et al. (1993) suggested that detachment of previously detained particles is a factor contributing to filter breakthrough. Such detachment occurs at specific shear velocity (Ives, 1985). At a filtration rate corresponding to the shear velocity, the particle may be detached and released to the suspension. It can then be recaptured in the lower portion of the media and retained. Higher filtration rates may cause more particle detachment and subsequent breakthrough. Turbidity removal efficiency was also influenced by orthokinetic flocculation within the media (Willson et al. 1980). At low filtration rates, such floc formation will be low and the removal efficiency may be reduced. A compromise between the above phenomena that results in efficient utilization of the filter bed for particle removal may have occurred at 8 m/h. Figure 2.5 suggests that the lowest variation of the average turbidity was evident in crushed quartz. Among the media studied, crushed quartz provided the lowest average turbidity at each filtration rate studied.

2.7.2 Consistency

One of the important concerns over the filter performance is its consistency of operation. Consistency of operation can be well defined by the standard deviation of the effluent turbidity distribution if the population is normally distributed. However, the turbidity data obtained in this study did not belong to a normally distributed population (Figure 2.3, Table 2.6) and the use of such concept will not be a viable option as a measure of consistency. However, the scatter of the data in effluent turbidity histograms (Figure 2.4) can be used to visually compare the consistency. A clustered histogram indicates a more consistent performance than a widespread histogram. From the histograms, the following conclusions could be drawn: (i) consistency is reduced at higher filtration rates; (ii) crushed quartz performed more consistently than the other types tested.

Alternatively, the range of the average turbidities of individual filter cycles (Table 2.6, Figure 2.5) can also be considered as a measure of consistency. Crushed quartz had the lowest variations in average turbidity at the filtration rates studied. Crushed quartz had a very high consistency at 8 m/h compared to the other two media types (Figure 2.5).

2.7.3 Filter Run Length

Filter run length (FRL) represents the terminal headloss or effluent quality at breakthrough depending on which criterion was used to terminate a filter run. It determines the frequency of filter backwash and associated costs. Figure 2.6 shows the average FRL with flow rates. All the filter runs in this study were terminated based on the limiting 1 m headloss criterion. At the high flow rate (12.5 m/h) all three types of filters investigated had FRL's of below 20 h. At the lower flow rate (3.5 m/h) the dual-media filter had a very long FRL. Crushed quartz and the existing media had a similar FRL, but approximately 40 percent of that of dual-media. Each filter type exhibited different trends in FRL with increased filtration rate. FRL of the dual-media and crushed quartz did not vary widely between 3.5 and 8 m/h. This indicates that until at least 8 m/h, the filter bed was not significantly exhausted (not enough pore clogging to advance the limiting headloss and turbidity breakthrough) for crushed quartz and dual-media filters (particle capture was generally found at the top quarter of the filter bed). For existing media, the FRL decrease with filtration rate increase was almost proportional. Longer FRL for dual-media filter with sand and anthracite was obvious because half of the filter bed contained anthracite of 200% of the sand size tested. This would increase the overall bed porosity.

2.7.4 Water Production Capacity

Water production capacity (WPC) governs the capacity and the operating costs of the filtration plant. Though WPC is the product of FRL and the filtration rate (Table 2.6), it will not have the same trend as FRL (Figure 2.6). Low filtration rates may give longer FRL and high filtration rate may result in shorter FRL. Depending on their magnitude, the WPC may follow a different trend than that of FRL. With increased filtration rate, the WPC of the existing filter media decreased (Figure 2.7).

The capacity of crushed quartz and dual-media filters increased between 3.5 m/h and 8 m/h, but declined afterwards. The increase in production capacity at 8 m/h was greater for the dual-media (approx. 300 percent). The trend indicates a possible optimum filtration rate for crushed quartz and dual-media filtration. At 12.5 m/h, due to increased headloss, the production capacity decreased.

2.7.5 Comparison by Factorial Experimental Analysis

Factorial experimental design (Davies, 1954; Box et al. 1978) was adopted to study the effects of many variables and their interactions at one time. In this study, the responses to be investigated were average effluent turbidity (TURB), WPC and FRL. The key assumption in factorial experimental analysis is that the population is normally distributed and has constant variance. The skewness of the turbidity distributions, probability plots (Figure 2.3) and histograms (Figure 2.4) suggest that the observed data are not normally distributed. In addition, based on the Bartlett's test (Kennedy and Neville, 1976) results, the estimated normal variances were found to be non-homogeneous and correlated with the average. Therefore, appropriate transformations, which were required to stabilize the variances, were estimated (Box et al. 1978). Additional normality tests such as Pearson's test (Johnson, 1949), Shapiro-Wilk test (Hahn and Shapiro, 1967) and tests for homogeneity of variances such as Levene's test (Jobson, 1991) and Bartlett's test were performed. The transformations which best transform the data normal and stabilize variances were established as:

$$Y'_{TURB} = (Y_{TURB})^{-0.4} \qquad [2.1]$$

$$Y'_{FRL} = (Y_{FRL})^{-0.2} \qquad [2.2]$$

$$Y'_{WPC} = (Y_{WPC})^{-0.3} \qquad [2.3]$$

Where Y= observed data and Y'= transformed data.

In general, factors that could affect the response were the filtration rate, influent turbidity, water temperature, filter media type, size and depth, and particle size. Filtration rate [X1] and the filter media type [X2] are considered as main variables because the main purpose of this study was not to optimize filtration but to compare different filter types and the lack of control over influent quality and temperature. Two levels (+1(high) and -1(low)) of the variables were considered in this study (2^2 factorial design). Filtration rates of 3.5 m/h and 12.5 m/h were considered for the factorial analysis. Among the three media types under investigation, two were considered at a time. Table 2.7 describes the experimental set-up for the factorial experimental analysis of the transformed data.

The effect of a change in the level of the variable is the change of response (Y) produced. Many methods to calculate the effects are presented in the literature (Davies, 1954; Box et al. 1978; Box and Hunter, 1961). Effect of each transformed variable (X1, X2) and the interaction (X12) are shown in Table 2.8. It should be noted that the factorial experimental principles adopt a linear model for calculating the effects. No optimization is possible without additional sequential experiments. Negative effect implies a drop in the response with the increase in variable level.

It should be highlighted that Tables 8 indicates the trend between 3.5 m/h and 12.5 m/h filtration rates. To compare the effect of the two different types of filter media, the effect of X2 can be investigated. For example, the effect of X2 on FRL is 0.08 when the filter media type changes from B (-1 level) to C (+1 level). This indicates that when the level is changed from B to C, FRL decreased (due to the negative power transformations, positive effect implies a drop in the response with the increase in variable level). Table 2.9 represents the summary of logical interpretation of the factorial analysis for the media types. Results tend to indicate that the average turbidity of crushed quartz is the best (lowest of the three media tested) but its WPC and the FRL were the lowest. The dual-media outperformed the other two types of media in these categories. It is also understood that the FRL and WPC for crushed quartz and the existing media are not substantially different.

2.8 Conclusions

Results show that use of statistical concepts beyond simple averages are needed in evaluating filter performance since the observed data are not normally distributed. The use of statistical plots, such as probability plots and frequency histograms, is better than using the turbidity profiles alone. Turbidity histograms are also useful for comparison of the average and consistency of turbidity data by visual interpretation. Probability plots are necessary to confirm the compliance to effluent turbidity standards for the recommended percentage of operating time as well as to check the normality of data. Skewness of the effluent turbidity distribution is also a valuable tool for assessing the risk or uncertainty of the change in the average turbidity and for confirming the normality. Such deviations from normality can be corrected by appropriately transforming the observed data. Different transformations were required for turbidity, FRL and WPC.

From Phase I of the study, approximately 50 percent improvement of filtrate turbidity and filter run lengths were observed with warm (13°C) water when compared to cold (< 5°C) water. Screening test results indicate that both the crushed quartz media and the dual-media (sand and anthracite) with polymer addition performed better than the existing filter media. All filter run lengths in this study were limited by the headloss criterion (≤1 m). The filtrate turbidity values show that the turbidity of all three filter types investigated in the second phase of the study never violated the 1993 licence requirement for water treatment plants during the operating cycles. However, their individual performances were found to vary at different filtration rates. For crushed quartz and dual-media filters, respective minimum average turbidity, maximum WPC and FRL were achieved at 8 m/h, indicating the possible existence of an optimum filtration rate which compromises between shear detachment and orthokinetic flocculation within the media. Histograms and the variation of the average turbidity suggest that the crushed quartz filter media exhibited the most consistent operation. For all three types tested, the consistency was reduced at 12.5 m/h. Comparison of filter media based on factorial experimental design principles suggests that the average turbidity of crushed quartz is the best (lowest value of the three media tested) but its WPC and the filter run length were the lowest. The dual-media outperform the other two types with respect to WPC and FRL which are similar for crushed quartz and the existing media.

2.9 Media Selection

Though dual-media produced more water during a filter cycle and satisfied the turbidity legislation, its use in the existing filters at Rossdale water treatment plant is restricted by inadequate full scale filter depth which could not be modified to accommodate the anthracite expansion during backwash. In addition, dual-media filter quality is borderline to the plant operating criterion at Rossdale water treatment plant (< 0.1 NTU) while crushed quartz provided turbidities well below the criterion. Though the FRL of the crushed quartz was 40 to 60% lower than the dual-media (Table 2.6), it was comparable to that of the existing mono-media. The above results suggest that the use of crushed quartz as filter media in place of the existing filter sand would improve the effluent turbidity to meet the stringent quality goals at normal filtration rates under the existing physical conditions of the filters. This is especially true when considering the normal operating filtration rate is in the range of 8 m/h. Further studies on the effects of polymer addition, hydraulic transients, filter ripening characteristics and physical characteristics may be conducted to make a complete evaluation of crushed quartz media.

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Table 2.1 Violations of the 1993 Licensing Requirements

Filter No.	Violation (March to August 1991)	
	% Turbidity*<1	Max. turbidity >1
1	96,	
2	98,	2.6, 2.3
3	98,	3.8,
5	96,96,98.6,99,99	3.1
6	89,83	3.3
8	98,88	3.4,3.5,2.9,2.7
9	99,98,87	3.5,2.0

* based on two-hour interval turbidity data during a day

Table 2.2 Filter Media Description - Phase I

Col. No.	Media Description	Layer Depth (mm)	ES (mm)	UC
F1	Existing filter sand	750	0.61	1.34
F2	Rounded silica sand	750	.50/.55	<1.4
F3	Rounded silica sand *polymer added*	750	.50/.55	<1.4
F4	Crushed Quartz	750	.50/.55	<1.4
F5	Dual-media/*polymer*			
	Rounded sand	425	.50/.55	<1.4
	Anthracite	325	1.1/1.2	<1.4
F6	Dual-media			
	Rounded sand	650	.50/.55	<1.4
	Garnet sand	100	.25/.30	<2.0

Table 2.3 Filtrate Turbidity At 7 m/h Filtration Rate (April-August 1991)

Column no.	Filtrate Turbidity (mean ± stdev.), NTU				
	April	May	June	Jul/Aug.	Grouped
F2	.081±.0548	.118±0509	.057±0421	.034±0145	.073±0457
F3	.069±.0583	.063±.0436	.052±.0303	.029±.0110	.053±.0421
F4	.065±.0297	.066±.0152	.054±.0128	.035±.0084	.055±.0193
F5	.081±.0302	.085±.0274	.073±.0111	.044±.0039	.071±.0226
F6	---	---	---	.044±.0150	

F6 : Existing filter media (replaced in July 1991)

Table 2.4 Filter Media Headloss and Filter Run Length

Column no.	Type of media	CBHL, m		FRL, h	
		Cold	Warm	Cold	Warm
F2	Round sand	0.470	0.220	20	42
F3	Round sand + polymer	0.520	0.270	14	31
F4	Crushed quartz	0.240	0.140	44	69
F5	Sand/anthracite + polymer	0.260	0.160	46	73

CBHL: Clean Bed Head Loss FRL: Filter Run Length

Table 2.5 Summary of Shock Test Results

Column no.	Type of media	Effluent Turbidity		
		Initial	Maximum	Change
F2	Round sand	0.040	0.234	0.194
F3	Round sand + polymer	0.031	0.120	0.089
F4	Crushed quartz	0.038	0.045	0.007
F5	Sand/anthracite + polymer	0.053	0.062	0.009
F6	Existing filter media	0.044	0.957	0.913

Table 2.6. Summary of Results- Phase II

Filtn. Rate	No.of Runs	Effluent Turbidity					Influent Turbidity		WPC mean	CBHL mean	FRL mean (range)
			Run average								
(m/h)		No.of Data	Low (NTU)	High (NTU)	Mean (NTU)	skew.	max. (NTU)	mean ± stdev. (NTU)	(m^3)	(m)	(h)
						Anthracite/sand dual-media					
3.5	16	7213	0.075	0.218	0.114	3.1	29	10.21 ± 4.09	6.0	0.16	97.7 (83 - 110)
8	12	8696	0.050	0.112	0.082	-0.2	20	10.56 ± 3.17	14.0	0.18	98.8 (92 - 108)
12.5	14	2606	0.100	0.340	0.239	1.07	19.7	8.01 ± 3.3	3.1	0.45	13.8 (9 - 22)
						Crushed quartz mono-media					
3.5	24	6752	0.037	0.069	0.052	9.75	29	10.21 ± 4.09	2.3	0.19	37.3 (23 - 50)
8	7	3707	0.044	0.048	0.045	2	20	10.56 ± 3.17	6.4	0.18	45.2 (35 - 55)
12.5	13	1653	0.052	0.176	0.094	4.4	19.7	8.01 ± 3.3	1.8	0.48	8.1 (3 - 14)
						Existing filter sand mono-media					
3.5	17	5375	0.054	0.116	0.079	7.18	29	9.42 ± 3.97	2.7	0.20	44.3 (32 - 62)
8	9	1703	0.103	0.209	0.143	2.43	20	10.56 ± 3.17	2.3	0.31	16.6 (11 - 23)
12.5	6	518	0.150	0.406	0.250	1.76	19	12.16 ± 3.41	1.5	0.47	6.8 (4 - 10)

Table 2.7. Factorial Experimental Analysis For Comparison

Filtration Rate X1 (m/h)	Media Type* X2	Level			Response (Y'^{**}), Transformed from Table 2.6.		
		X1	X2	X12	TURB (NTU)	FRL (h)	WPC (m^3)
		To compare media types B and C					
3.5	B	- 1	-1	+1	2.38	0.04	0.58
3.5	C	- 1	+1	- 1	3.26	0.49	0.78
12.5	B	+1	- 1	- 1	1.77	0.59	0.72
12.5	C	+1	+1	+1	2.57	0.66	0.84
		To compare media types C and D					
3.5	D	- 1	- 1	+1	2.76	0.47	0.74
3.5	C	- 1	+1	- 1	3.26	0.49	0.78
12.5	D	+1	- 1	- 1	1.74	0.52	0.56
12.5	C	+1	+1	+1	2.57	0.66	0.84
		To compare media types B and D					
3.5	D	- 1	- 1	+1	2.76	0.47	0.74
3.5	B	- 1	+1	- 1	2.38	0.04	0.58
12.5	D	+1	- 1	- 1	1.74	0.52	0.56
12.5	B	+1	+1	+1	1.77	0.59	0.72

*Media types:- B: Anthracite/sand dual-media, C: Crushed quartz, D: Existing filter media

**Transformation to stabilize the variances as given in Equation 2.1, 2.2 and 2.3, respectively.

Table 2.8. Results of Factorial Analysis: Effects and Interaction (transformed scale)

To compare	Crushed quartz & Dual-media			Dual-media & Existing filter media			Crushed quartz & Existing filter media		
Y	TURB	FRL	WPC	TURB	FRL	WPC	TURB	FRL	WPC
Effect of									
X1	-0.65	0.18	0.10	-0.81	0.20	0.14	-0.85	0.19	0.10
X2	0.84	0.08	0.16	-0.17	-0.08	-0.16	0.67	0.00	0.00
X12	-0.04	-0.01	-0.03	0.20	-0.01	-0.01	0.17	-0.02	-0.04

Table 2.9. Interpretation of Factorial Experimental Analysis

To compare	B and C	D and B	D and C	Overall
Effluent Turbidity	B>C	B>D	D>C	B>D>C
Filter Run Length	B>C	B>D	D=C	B>>D=C
Water Production Capacity	B>C	B>D	D=C	B>>D=C

Media types:-
B. Anthracite/sand dual-media, C: Crushed quartz mono-media, D: Existing filter mono-media

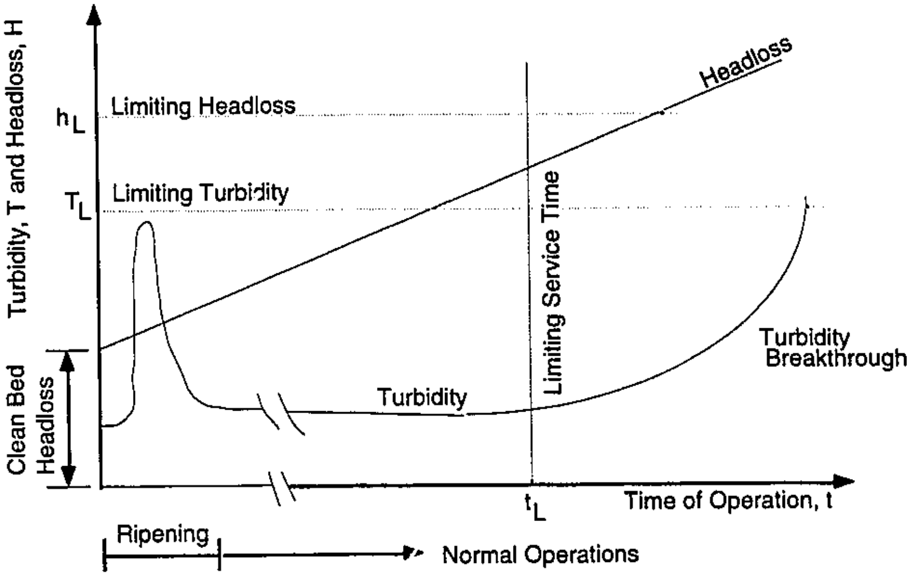

Figure 2.1 Typical Filter Run Characteristics and Termination Criteria

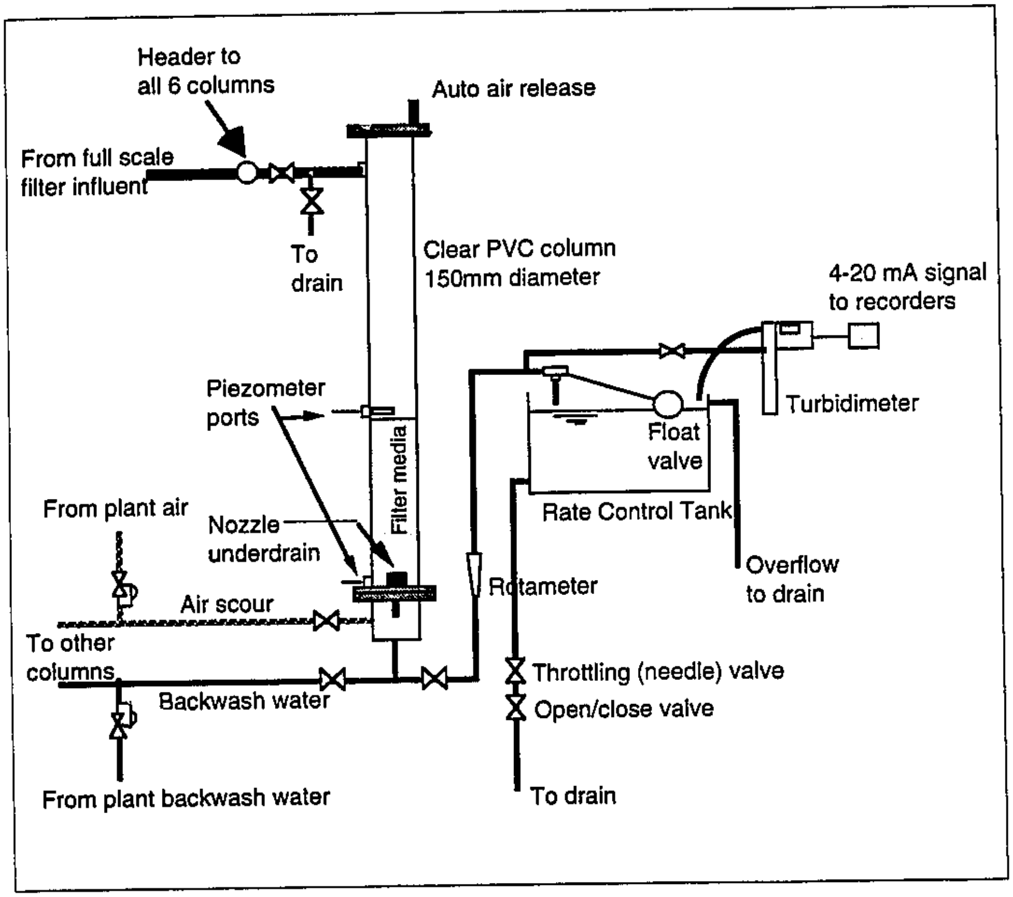

Figure 2.2 Filtration Pilot Plant (one of six columns shown)

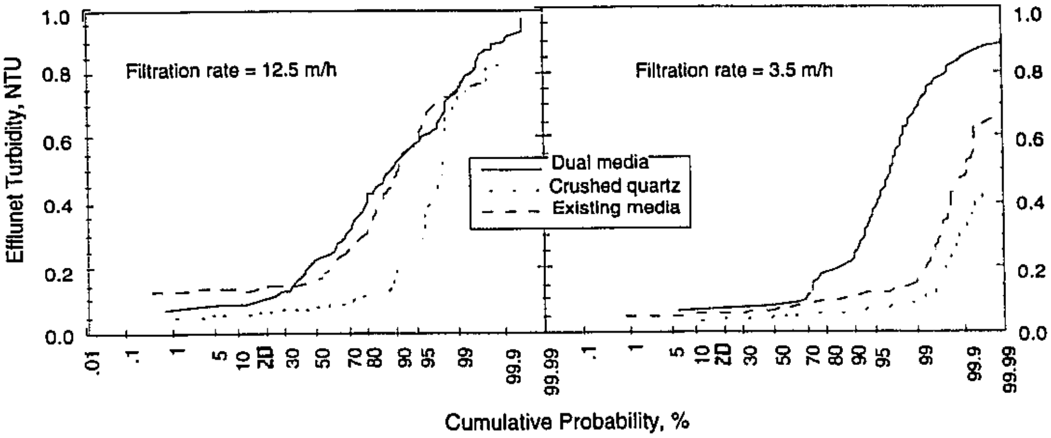

Figure 2.3 Probability Plots of Effluent Turbidity

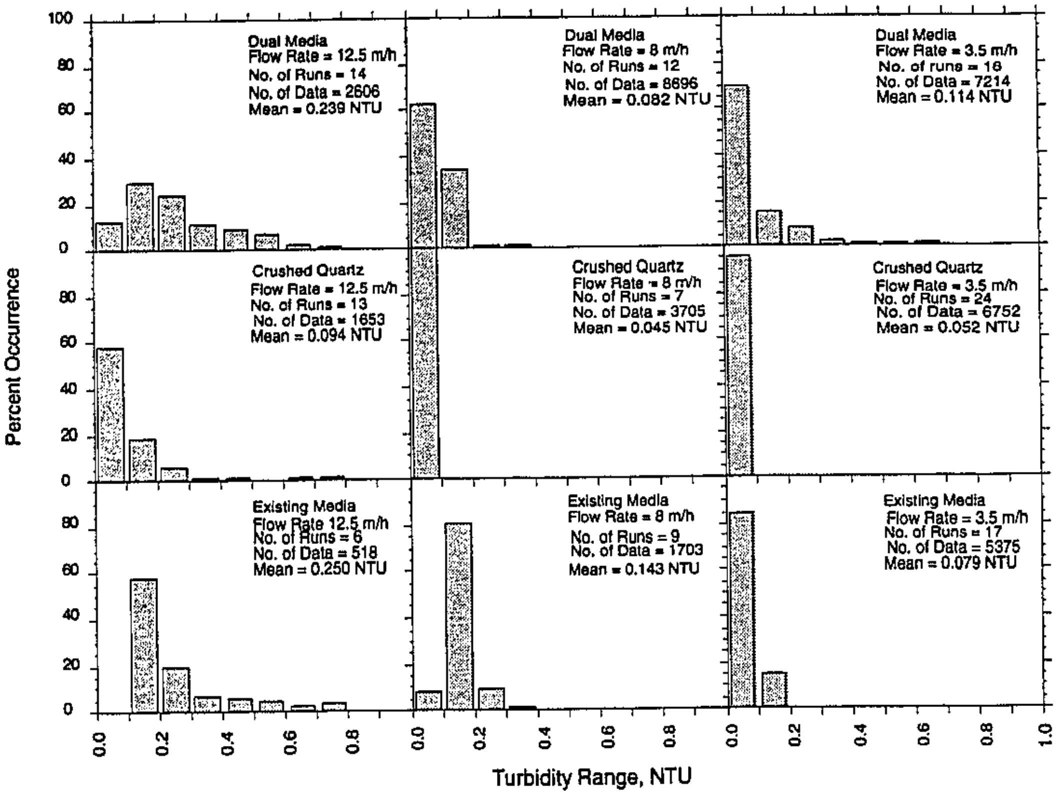

Figure 2.4 Frequency Histograms of Effluent Turbidity

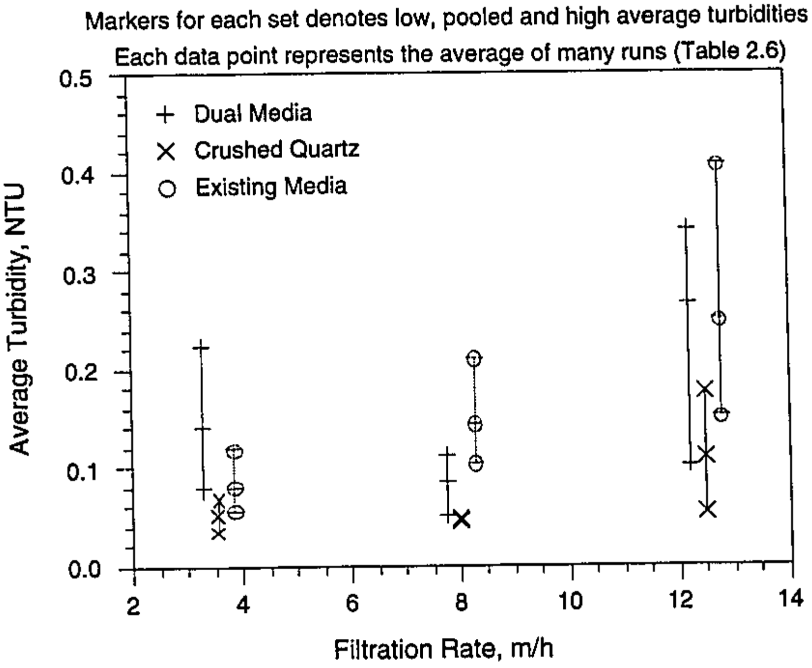

Figure 2.5 Comparison of Average Turbidity

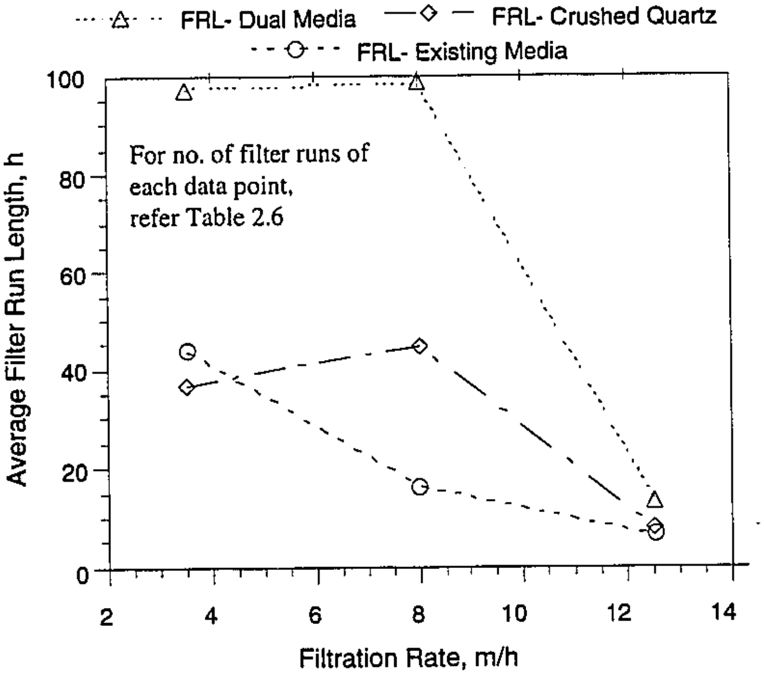

Figure 2.6 Comparison of Filter Run Length

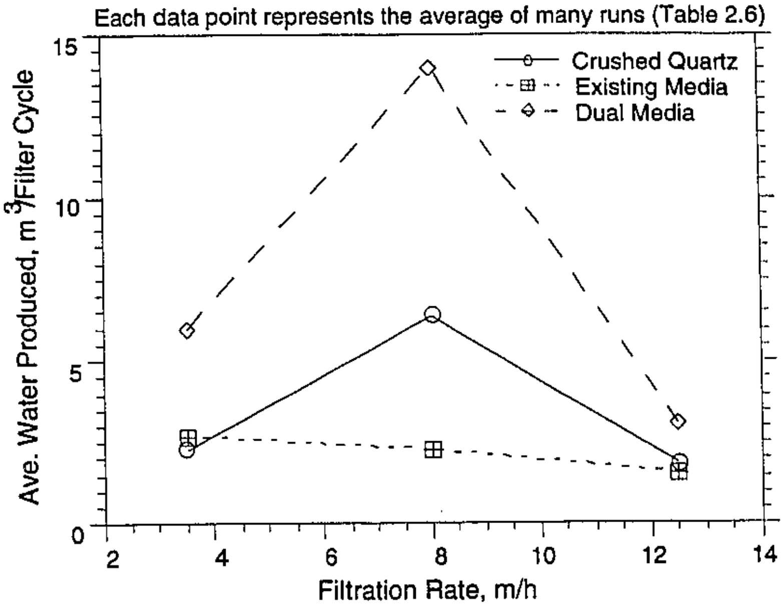

Figure 2.7 Comparison of Water Production Capacity

Chapter 3

Evaluation of Filter Media for Upgrading Existing Filter Performance

3.1 Introduction

Understanding of the association of the turbidity with many adverse public health effects has prompted the implementation of progressively stringent turbidity guidelines for drinking water (Suthaker et al. 1995). Though improvements on each of the individual unit processes of water treatment assist in reducing turbidity, upgrading the filtration process, which is the final physical process for turbidity removal in a conventional water treatment, will be very effective in improving the finished water quality if the pretreatment process is already optimized.

Presented is a study which evaluated filter media aspect of an upgrading to existing filters at the Rossdale water treatment plant in Edmonton, Alberta, Canada. One alternative for filter improvement is the use of a filter media capable of higher particle removals. Filter sand that contains a mixture of materials with different origins and shapes can lead to a non-uniform filter bed structure depending on the settling characteristics of individual sand particles. The shape of the media can also impact performance. Greater angularity of filter media results in larger bed porosity (Cleasby and Fan, 1981). In addition, charge concentration on the angular edges of the media may increase particle attraction to the media. Selection of a filter media whose characteristics result in: i) reduced effluent turbidity; ii) consistent operation; iii) ability to withstand any sudden influent variation and iv) abrasion resistance for increased media durability, will improve a water treatment facility's ability to satisfy more stringent licensing requirements and in-plant guidelines.

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In addition to the above factors, some site-specific constraints had to be considered in the filter upgrade. The available hydraulic head for filter operations was limited. As the location of the underdrain system and influent weirs was limited by the existing filter construction, during backwash, the selected media expansion was limited by the existing weir level to prevent media loss.

Water treatment at the Rossdale water treatment plant consists of conventional water treatment processes (capacity 290 MLD) consisting of coagulation, flocculation, sedimentation, softening, filtration and disinfection. Raw water is obtained from the North Saskatchewan River and is heated during cold weather. The recarbonated softening clarifier effluent is conveyed to filters through a stilling basin with chlorine and fluoride addition. The filters contained silica sand (effective size ES = 0.61 mm, uniformity coefficient UC = 1.34) and were operated in a constant rate control method.

The Provincial Government of Alberta issues the licence to operate water treatment plants which specifies water quality standards to be met by the Rossdale water treatment plant. Among other requirements, the 1993 Rossdale water treatment plant licence to operate specified: (i) individual filter turbidity to be less than 1 NTU, 99% of the operating time and never exceeding 2 NTU; and (ii) daily arithmetic average of combined filter turbidity not to exceed 1 NTU. Operating data for the existing full scale filters for the period of March 1991 to August 1991 indicated possible violations of the 1993 licensing requirements. In addition, the concern with providing a better quality product lead to the in-plant turbidity standard of 0.1 NTU. Many studies have been conducted earlier to optimize the pretreatment process for different seasonal raw water qualities. These prompted the need to upgrade the filters at the Rossdale water treatment plant. Possible alternatives that were considered to improve filter performance included: i) the use of a better type of filter media which could withstand influent turbidity spikes and which was tolerant to sudden filtration rate changes or shocks while satisfying more stringent effluent standards; and ii) changing the control of the filters to declining rate.

A pilot plant filter study was conducted to provide guidance toward achieving the above goals. The pilot plant was built to match the bed depth and weir elevations of full scale filters at Rossdale water treatment plant. The study reported herein only deals with the filter media aspects. Due to the restrictions on the existing filter design, the optimization of media size and filter bed depth were not conducted. A previous study involved screening tests on a number of different types of media (Poole, 1992). Based on its results and recommendations, use of crushed quartz filter media or use of anthracite/rounded sand dual-media were found to be capable of improving filter performance. Further experiments were required to choose one of the above filter media for the use in full scale filters. As a result, a subsequent study was conducted on the performance of these two types of media at different filtration rates. Statistical concepts were used to evaluate the filter performance based on effluent turbidity, Filter Run Length (FRL) and Water Production Capacity (WPC). The results indicated that the crushed quartz filter media in place of the existing filter media would improve filtration and meet the stringent effluent quality goals at normal filtration rates and prevailing physical and operational limitations of the full scale filters (Suthaker et al. 1995).

Polymer is generally added to coagulated and lime softened water as filter aid to improve effluent quality (Cleasby et al. 1989). Since crushed quartz as filter media has not been studied earlier, it was important to understand its performance during polymer addition, sudden filtration rate variations and filter ripening sequence (FRS). Also, filter media generally undergoes abrasion during filter backwash cycles. Abrasion resistance of the crushed quartz was thought to be of importance as its performance can be related to its very angular shape thus resulting in high porosity and a very tortuous path the water must follow through it. There was some concern whether crushed quartz would become more rounded due to abrasion and behave like rounded sand which was found to be less effective on its own. Therefore, abrasion resistance of the crushed quartz needed to be considered and compared with the other media types.

This paper describes a comparative study of the abrasion resistance, effects of polymer addition as filter aid, performance during sudden filtration rate changes, the FRS of the crushed quartz and compared its performance with an anthracite/sand dual-media and with the existing full scale filter media. Statistical tools were used to evaluate the significance of comparisons from a comprehensive database of filter performance. Factorially designed experiments facilitated the use of half-normal plots to study the significance of the effects of filtration rate, polymer dose and media type on filter performance.

3.2 Pilot Plant Description

Six clear PVC columns of 150 mm diameter were used as the filters (Figure 3.1). Due to restricted headroom in the required location for the pilot plant, a closed-top construction had to be employed. Influent is drawn from the feed water channel of the full scale filters. Constant rate control was achieved by a constant level (float controlled) header tank as suggested by DiBernardo and Cleasby (1980) providing a constant head on a throttling, manual needle valve.

A polymer feed system was installed with a multi-tube peristaltic pump. Polymer was injected into the feed pipes to the column against the flow. Stock solutions of the polymer were prepared once a week to prevent aging and were diluted to working solution on a daily basis. Filtered water turbidity was measured by 'flow-through' low range turbidimeters (Hach® model no. 1720C) which are similar to those used with the full scale filters. The 4 to 20 mA outputs from the turbidimeters were recorded by a datalogger from which the data could be downloaded to a computer. The turbidimeters were calibrated every month by checking meter readings with laboratory measurements of turbidity. The turbidimeters were in very good calibration throughout the test period (coefficient of variation of 3.5%).

To compensate for the lack of influent quality control when using plant water, each experimental condition was operated for a reasonably long period which includes a sufficient number of filtration cycles to obtain a good representation of filter performance.

3.3 Experimental Procedure

3.3.1 Pilot Plant Operations

Different filter media configurations were simultaneously loaded in all pilot columns. Two columns contained crushed quartz mono-filter-media (750 mm deep). Two columns contained rounded sand (325 mm) /anthracite (425 mm) dual-filter-media. The other column was loaded with existing full scale plant filter media (750 mm) as a control experiment to compare the existing filter performance. Filtration rates used in this study were 12.5, 8 and 3.5 m/h which represent the widest range of filtration rates that could occur in the full scale filters. Other work reported in the literature suggests that polymer doses of up to 0.1 mg/L could be used as filter aid to enhance filter performance. In order to investigate the effects of polymer addition, 0, 0.02, 0.06 and 0.1 mg/L of polymer (PERCOL LT 20®, a non-ionic polyelectrolyte) doses were studied as a filter aid.

Effluent turbidity was recorded at five minute intervals during regular filter operations and every six seconds during filter ripening sequence. Water levels of the installed piezometers were recorded every two hours by a still camera. Headloss was calculated from those levels. A filter run was terminated when the headloss reached 1 m (maximum available headloss for full scale filters) or the effluent turbidity continuously exceeded 1 NTU. A factorial designed experiment (Box et al. 1978) was used to study all major influencing parameters. The order of the experiments was randomized to distribute the experimental errors over the filters. Though randomization prevents any side-by-side comparison, it spreads the errors caused by seasonal influent quality variations. Numerous filter runs were completed at each operating condition to ensure that the data was representative of the actual performance.

3.3.2 Abrasion Resistance Tests

Incipient fluidization during backwash may create collisions between individual filter media particles, thereby causing abrasion. Simultaneous air scour and sub-fluidization water wash during backwash also causes abrasion (Cleasby et al. 1977; Amirtharajah, 1978; Hewitt and Amirtharajah, 1984; Fitzpatrick and Ives, 1989). Abrasion resistance is a very important consideration in the durability of filter media. Filter media with high abrasion resistance is preferable. There was some concern that the angular nature of the crushed quartz would be worn down with time. As a result, abrasion tests were originally done to see if the crushed quartz was durable enough. The tests were also used to compare the durability of the filter media tested. Moh hardness is generally used to assess the abrasion resistance. However, due to difficulties in performing this test and inadequate correlations reported in the literature, alternative test procedures are still under investigation (AWWA, 1989). Earlier, loss of filter media was monitored during long periods of filter operation with many backwashes to characterize abrasion resistance (Cleasby and Lorence, 1978: Ives, 1990). However, long term predictions may not be possible in pilot plant studies. Though standard protocols are not available, some of the existing physical tests, which are discussed below, can be used to compare the abrasion resistance.

3.3.2.1 Particle size distribution (PSD)

Due to abrasion, media may break into smaller size which could be lost during backwash. This will alter the PSD. The conventional method of determining PSD is by sieve analysis. At the end of the study, filter media were taken from the pilot columns, dried, and sieve analyses were performed. Results were compared with that of the fresh filter media for specific characteristics of the PSD such as the Effective Size (ES) and Uniformity Coefficient (UC).

3.3.2.2 Friability test

Friability of a substance is calculated by assessing the portion of material that are usable after grinding. This is commonly used for coal and can be adopted for filter media (Degremont, 1979). Sieve analysis was completed on a 35 mL sample and was placed into a cylinder (40 mm I.D. and 100 mm height) which contained 12 mm diameter steel balls (total of 18). The cylinder was then rotated at 25 rpm for fifteen minutes (i.e., 375 revolutions). Then the sample was removed and a second sieve analysis was performed. The sample was then returned to the cylinder, rotated for another 15 minutes (750 revolutions, total) and a third sieve analysis was performed. Friability of a material is given by,

$$\text{Friability (\%)} = \frac{10 \bullet (x - 10)}{9} \qquad [3.1]$$

where, X represents, after crushing, the percentage of material by mass of smaller size than the initial ES of the material. Friability is calculated after 375 and 750 revolutions using Equation 3.1.

3.3.2.3 Acid solubility

This test is performed by immersing a known weight of filter media into 1:1 hydrochloric acid until the acid soluble materials are dissolved. Termination of dissolution can be determined when the gas bubble forming ceased. Then the sample is washed and dried to constant weight. The acid solubility is then calculated by the percentage weight loss (AWWA, 1989).

3.3.2.4 Scanning electron microscopy (SEM)

Some of the filter media surface characteristics such as angularity, surface porosity and appearance will change due to abrasion during backwash. Though the above described tests may provide overall abrasion resistance, they may not indicate what actual changes occurred in the media surface. Scanning electron microscope (Hitachi®, Model S-2500) images were investigated for surface depositions and shape changes of the media. Used media samples were collected after backwashing to remove the captured particles attached to the media. The media samples were dried to the critical point to eliminate forms of distortion such as shrinkage and wrinkles that ordinarily might occur if the samples were air-dried. The media was then 'gold spatter coated' to increase the contrast of the specimen when used in the scanning electron microscope. Stereoscopic views of numerous filter media specimen were analyzed and representative SEM photographs were taken. In order to study the effect of surface depositions on the media, the used filter media samples were acid-washed in 1:1 hydrochloric acid to remove the surface depositions and their SEM images were analyzed.

3.4 Results And Discussion

3.4.1 Pilot Plant Performance

The summary of the pilot plant results is given in Table 3.1. Figure 3.2 to Figure 3.4 respectively depict the variation of average turbidity, FRL and WPC (volume of water processed during one filter cycle). The effects of filtration rate and polymer dose on filter performance were analyzed. Filter performance was characterized by average effluent turbidity, FRL and the WPC. FRL is determined either by reaching the available terminal headloss or effluent quality at breakthrough depending on which criteria dictated the termination of a filter run. WPC is an indication of combined effects of filtration rates and FRL. Although WPC is based on the product of FRL and the filtration rate [i.e., $FRL = f_1(v)$, $WPC = a \cdot v \cdot FRL = a \cdot v \cdot f_1(v) = k \cdot f_2(v)$; where v = filtration rate (m/h), a = filter area (m^2), $f_1(v)$, $f_2(v)$ = functions of v], it will not have the same trend as FRL (Suthaker et al. 1995). Low filtration rates may give longer FRL and high filtration rate may results in shorter FRL. Depending on the magnitude of FRL which is dictated by the filtration rate, the WPC may have a different trend than that of FRL in constant rate filtration. WPC also relates to the economy of operation.

The pilot plant results were analyzed in a comparative manner based on: (i) performance of each media type for every operating condition (filtration rate and polymer dose); (ii) performance at each filtration rate; and (iii) effect of polymer addition at each filtration rate. Standard statistical methods were used to assess the significance of the data obtained.

3.4.1.1 Significance of pilot plant results

When comparing two parameters showing variations about their respective average (which is expected in a pilot plant study of this nature with long term observations and minor influent quality variations), making conclusions based on the numerical comparisons such as simple average turbidity, FRL or WPC alone may not be adequate. It requires the use of some statistical concepts such as t-test (Kennedy and Neville, 1976) beyond simple averages to establish the significance of such differences. The t-test is based on the assumption that the data are normally distributed. However, analysis of filtration data from a previous study (Suthaker et al. 1995) without polymer addition suggested that the filtration data were not normally distributed. In addition, the skewness of the filtrate turbidity data (Table 3.1) and the results of the Bartlett's test (Kennedy and Neville, 1976) of homogeneity of the variances also reiterate such non-normality of filtration data obtained from this study. Therefore, appropriate transformations, which were required to stabilize the variances, were estimated (Box and Cox, 1964). Additional normality tests such as Pearson's test (Johnson, 1967), Shapiro-Wilk test (Hahn and Shapiro, 1967) and tests for homogeneity of variances such as Levene's test (Jobson, 1991) and Bartlett's test were performed. From the above tests, the transformations which best transform the data normal and stabilize variances were established as Equations 3.2, 3.3 and 3.4 for turbidity (TURB), FRL and WPC, respectively.

$$Y'_{TURB} = (Y_{TURB})^{-0.4} \qquad [3.2]$$

$$Y'_{FRL} = (Y_{FRL})^{-0.2} \qquad [3.3]$$

$$Y'_{WPC} = (Y_{WPC})^{-0.3} \qquad [3.4]$$

where, Y = observed data; Y' = transformed data

The t-tests were performed on the averages of the transformed observations to establish the significance level (α) of the difference between two observations. Conclusions were drawn from the comparisons which were significantly different at a significance level less than 0.05.

3.4.1.2 Effluent turbidity

For the anthracite/sand dual-media and crushed quartz, the lowest turbidity was experienced at 8 m/h (Figure 3.2). One possible explanation for this phenomenon may be the existence of a limiting flow compromising between shear detachment and orthokinetic flocculation within the media thus resulting in removal being distributed through a greater depth of the media. Moran et al. (1993) suggested that detachment of previously detained particles is a factor contributing to filter breakthrough. Such detachment occurs at specific shear velocity (Ives, 1985). At a filtration rate corresponding to the shear velocity, the particle may be detached and released to the suspension which can be recaptured in the lower portion of the media and retained. Higher filtration rates may cause more particle detachment and subsequent breakthrough. Turbidity removal efficiency was also influenced by orthokinetic flocculation within the media (Willson et al. 1980). At low filtration rates, such floc formation will be low and the removal efficiency may be reduced.

Effluent turbidity was increased by polymer addition at 8 m/h filtration rate (α = 0.005). At 3.5 and 12.5 m/h, polymer addition on anthracite/sand dual-media and crushed quartz, results were not conclusive. This suggests that polymer addition may not considerably improve effluent turbidity at the filtration rates tested with the mixing provided in the pilot plant. Further polymer mixing studies are required to better evaluate the effect of polymer addition.

In all experimental conditions, effluent turbidity of the crushed quartz was the lowest ($\alpha < 0.004$) except for 0.1 mg/L of polymer addition ($\alpha < 0.2$). Average turbidities of the existing media were greater than that of crushed quartz. Reduced capture efficiency of the anthracite portion may have caused higher average turbidities for the dual-media than in crushed quartz.

3.4.1.3 Consistency of operation

If the data are normally distributed, its standard deviation can be used to characterize the consistency or reliability of filter operation around the average turbidity (i.e., lower the standard deviation, the more consistency of operation). Since the data in this study are not normally distributed, the range of average turbidity (Figure 3.2) was used to compare the consistency of operation. In general, the consistency was reduced at higher filtration rates. No clear conclusion can be made about the effect of polymer addition on consistency. Without polymer addition, the highest degree of consistency was experienced in crushed quartz at 3.5 and 8 m/h filtration rates and it was found to result in poorer consistency at 12.5 m/h but, better than the other media types.

3.4.1.4 Filter run length (FRL)

Among all the media types tested, FRL (Figure 3.3) of the anthracite/sand dual-media was the best ($\alpha = 0.012$) except for that of 8 m/h (0.06 mg/L polymer) where the results were inconclusive. At 12.5 m/h, both dual-media and crushed quartz had FRL's of below 20 hrs. At lower filtration rates, all filters had long FRL. Maximum FRL for both crushed quartz ($\alpha = 0.001$) and anthracite/sand ($\alpha = 0.094$) filters without polymer addition was obtained at 8 m/h. Polymer addition at 12.5 m/h filtration rate did not considerably change FRL. At 3.5 m/h, 0.1 mg/L polymer addition significantly decreased the FRL ($\alpha = 0.045$) from that with no polymer. This may be due to the fact that high filtration rates provide better mixing (velocity gradient) in the filters thus resulting in more uniform polymer action. At low velocities, inadequate mixing may have caused localized particle agglomeration and subsequent clogging of filters. This was evident in the top portion of the media where the captured flocs were seen blocking entry into the pores.

3.4.1.5 Water production capacity (WPC)

WPC (Figure 3.4) of the anthracite/sand dual-media was the best ($\alpha = 0.049$) among all the media types tested, except for that of 8 m/h (0.06 mg/L polymer) where the results were inconclusive. As for FRL, the maximum WPC for both crushed quartz and anthracite/sand filters was observed at 8 m/h without polymer addition ($\alpha = 0.031$). The effect of polymer addition on WPC was similar to that observed for FRL.

The above results can be used to compare the individual performance of the media types tested at different operating conditions. It is also possible to evaluate the effects of filtration rate, polymer dose and media type on the filter performance by analyzing the observed data based on factorial experimental principles. This will facilitate the design of further sequential experiments to optimize the filter performance in terms of effluent turbidity, FRL or WPC.

3.4.2 Factorial Experimental Analysis of Filtration Data

Use of statistical data analysis is very suitable for this study as the number of experiments and data are large. Factorial experimental design (Box et al. 1978; Davies, 1954: Box and Hunter, 1961) is primarily adopted to study the effects many variables and their interactions at one time. In this study, the responses to be investigated are average effluent turbidity, WPC and FRL. In general, factors that could affect the response are the filtration rate, polymer dose, influent turbidity, water temperature, filter media type, bed depth and media size. Since the main purpose of this study was not to optimize filtration but to compare different filter media types, and, due to the lack of control over influent quality and temperature, only the filtration rate, polymer dose and the filter media type were considered as main variables. Filtration rates of 3.5 and 12.5 m/h; polymer doses of 0.02 and 0.1 mg/L; and the media types of crushed quartz (type C) and dual-media (type B) were considered as variables. Center point replicates were studied at 8 m/h filtration rate and 0.06 mg/L polymer dose to estimate the pure experimental error.

The key assumption in factorial experimental analysis is that the population is normally distributed and has constant variances. Therefore, factorial analyses were performed on the transformed data according to equations ii, iii and iv respectively for TURB, FRL and WPC. Table 3.2 describes the experimental set-up for a factorial experimental analysis. The effect of a change in the level of the variable is the change of response (Y) produced. Many methods to calculate the effects are presented in the literature (Box et al. 1978; Davies, 1954: Box and Hunter, 1961). Effects of each variable (X1, X2, X3) are shown in Table 3.3. It should be noted that the factorial experimental principles adopt a linear model for calculating the effects. No optimization is possible without additional sequential experiments. A negative effect implies an increase in the response with the increase in variable level because of the negative power transformation.

It is also possible to investigate the variables which produce significant effects by using a half-normal plot (Daniel, 1959). The t-tests (Davies, 1954) were also used to interpret the significance of effects. The t-characteristic of an effect is given by the absolute ratio of the effect to the standard error of experiments. This is obtained from the center point replicates at 8 m/h filtration rate. From t-tests, it can be inferred that effluent turbidity is influenced by the main effects of filtration rate (X1), media type (X3) and its interaction with polymer dose (X23). However, the half-normal plot for TURB (Figure 3.5a) does not clearly distinguish significant effects. WPC (Figure 3.5b) is primarily influenced by media type (X3). FRL (Figure 3.5b) is influenced by the filtration rate (X1) and media type (X3). Similar results were obtained for FRL and WPC by the t-tests. From the effects of media type (Table 3.3), it can be seen that crushed quartz produced lower turbidity than the dual-media, however, its WPC and FRL were less. Polymer addition did not significantly influence the TURB, WPC and FRL.

3.4.3 Effect of Sudden Rate Changes

When a filter taken out of service for backwash or maintenance, a flow surge is experienced by the other filters, especially, in treatment plants with small number of filters. Changes in plant operational strategy may require a flow increase in the filters. Therefore, rate change tests were performed at the end of each experiment. During a sudden filtration rate change, large amounts of previously deposited material can be flushed through the filters causing effluent turbidity peaks. The amount of material flushed through the filter depends on the magnitude of the rate change. However, the amount of material flushed is independent of the duration of rate change (Cleasby et al. 1963). Table 3.4 summarizes the results of the rate change tests. During rate change, polymer addition tends to decrease the peak turbidity and the time required to recover to the original turbidity. Change in turbidity was the lowest for crushed quartz. Also, crushed quartz recovered to original turbidity quicker than the others. Among the media types tested, crushed quartz withstood sudden rate changes better than the others.

3.4.4 Filter Ripening Sequence (FRS)

When a filter is put to service after backwash, the particle remnants of the backwash water within the filter bed first enter the effluent stream. Since the filter bed is not matured at this time, influent particles also can make easy passage through the filter bed and reach the effluent stream. This will eventually result in initial effluent turbidity peaks. This peak turbidity is later decreased, and when it reaches a desired value (0.2 NTU, for Rossdale water treatment plant filters), the filter bed is considered mature. This phenomenon is called the FRS (Amirtharajah and Wetstein, 1980). The filter ripening characteristics can be used to compare the performances of different filter media. Figure 3.6 depicts the FRS for all the media tested at filtration rates of 3.5 m/h and 8 m/h in the pilot plant. The effluent valve opening in all the ripening studies was smooth but quick. Each data set in Figure 3.6 is the average of six different parallel FRS curves but with similar shape and peak value. The operating conditions (filter influent turbidity (3.2 NTU), water level of the rate controller before opening, rate of effluent valve opening (approx. 10 rpm)), except the filtration rates, were identical in all results shown in Figure 3.6. Crushed quartz performed the best among the media tested at both filtration rates while its peak turbidity did not exceed 0.2 NTU (in-plant turbidity guideline for the end of filter ripening). This may be due the improved capture efficiency of crushed quartz filter. Existing media exhibited very high peak turbidities (> 1 NTU) during ripening.

3.4.5 Abrasion Resistance

Table 3.5 summarizes the results of the abrasion resistance tests. Acid solubility results for all filter media types were under the maximum recommended standards of 5 % (AWWA, 1989). Acid solubility of the existing filter media was very large compared to the others tested. This could have resulted from the removal of surface deposits, accumulated during its long previous operation (approx. 7 years). Galvin (1992) reported the acid solubility of silica sand, used in filters treating prechlorinated, clarified and pH-adjusted (by lime addition) water, was found to increase with years of service and reached a maximum after 30 years due to accumulation of Mn, Fe, Al, Ca and Mg. The acid solubility of the anthracite was more than 5 times that of crushed quartz and rounded sand.

Changes in particle size distribution can be an indication of abrasion, media loss during backwash and detachment or formation of surface deposits (consisting primarily of calcium carbonate during filtration of lime-softened water). Since the filter media has been exposed to the natural environment for very long time before being put in the filters, the main cause for changes in particle size distribution may be the formation or detachment of the surface deposits. A previous study (Galvin, 1992) indicated that, the ES tend to decrease for about 15 years and then increase with the time of service. The UC increased initially, then stayed constant for some time after which it increased again. Such behavior was explained by the initial disappearance of smaller fractions during backwashing and the accumulation of deposits. In this study, the period of pilot plant operation was short and the observed changes in particle size could not be compared with the literature reported long-term observations. Within the study period, an increase in ES was observed for all media types, with rounded sand having the largest increase. A decrease in UC was also experienced. However, long term changes may differ from these results.

Friability values (Table 3.5) were in compliance with the literature (Degremont, 1979) recommended values (max. 20 % after 375 rev.; max. 35% after 750 rev.). Friability of the existing media was the lowest among the media tested. This is due to its longer service time, during which: (i) the weaker portion of the media deposits may be washed off; and/or (ii) the surface of the media was strengthened with deposits. Anthracite was found more friable than the other media. This can be a concern of efficient utilization of dual-media filters with anthracite, as it can crumble much earlier than the sand media. Break-up of anthracite will lead to smaller particles which will wash-out easier during backwash, causing media loss. Both crushed quartz and rounded sand exhibited higher abrasion resistance than the other media tested.

Representative photographs of fresh, used and acid-washed media surfaces obtained by SEM are shown in Figures 3.7 through 3.10. No fresh media was available for comparison of existing filter media. Figures 3.7a and 3.7b illustrate the existing filter sand surface clearly showing cracks (possibly the cracked deposits). However, SEM of the acid-washed existing media (Figure 3.7c) did not reveal any such cracks. This is an indication that the surface shown in Figures 3.7a and 3.7b may contain the cracked surface deposits which might have accumulated during its long term exposure to calcium carbonate, alum, polymer and suspended particles carried over from clarification, softening and recarbonation process. The magnified surface of crushed quartz is shown in Figures 3.8a, 3.8b and 3.8c. The surface of fresh crushed quartz was generally flat, with very little rake-like formation on it, as shown in the top right corner of Figure 3.8a. The very fine quartz particles, apparently attached to its surface, may be the remnants of the manufacturing (crushing) process. After the crushed quartz is put to service, the processing remnants were washed away and the surface appeared smooth with minute pores possibly containing the captured influent particles (Figure 3.8b). Indications of surface cracks were not evident in the used crushed quartz media surface, indicating less susceptibility of possible break-up of the media and subsequent media loss. Fresh rounded sand (Figure 3.9a) showed existing cracks. It also contained larger pores indicating larger available specific surface area than the crushed quartz. Abrasion of rounded sand tends to smooth the rough surface (Figure 3.9b). However, the surface cracks were still visible, similar to the fresh media. Therefore, it may be assumed that the cracks in the rounded sand were not induced by abrasion. Anthracite surface was generally smooth without cracks and contained remnant particles (Figure 3.10a). Used anthracite showed some surface crack developments with an extensive amount of particles attached to its surface indicating difficulty removing surface deposits during backwash (Figure 3.10b). Among the acid-washed media, both the existing filter sand (Figure 3.7c) and the rounded sand (Figure 3.9c) surfaces were rugged. This may have been due either to such original surfaces or to the acid attack. Crushed quartz surface was nearly unchanged by the acid attack (Figure 3.8c) showing the same surface features as in the fresh media. This suggests that the crushed quartz may retain its original shape during long term operation.

The particles attached to the media surface may arise from: (i) adhesion of influent particles which may be enhanced with polymer addition; (ii) chemical adsorption; (iii) physical adsorption; and (iv) extensive abrasion of the media causing remnants to adhere to its surface. Captured particle accumulation was evident in anthracite and rounded sand surface but little was seen in crushed quartz. Very large accumulations in anthracite may be partly due to higher bed expansion thereby reducing the abrasion and eventual particle detachment during backwash. Particle accumulation may not be desirable as it may reduce the filtering efficiency by blocking the surface pores. This would reduce the specific surface area and alter the physical attractive forces and chemical bonding characteristics. In view of particle accumulation from SEM photographs of the backwashed media, crushed quartz may provide efficient particle detachment during backwash.

3.5 Summary And Conclusions

All filter media types tested produced filtered water that complied with the current turbidity standards (< 1 NTU). Average effluent turbidities of the crushed quartz media were the lowest among those tested under all experimental conditions. This was also supported by the results of factorial experimental analysis. Reduced capture efficiency of the anthracite portion may have caused higher average turbidities for the anthracite/sand dual-media than for the crushed quartz. Consistency of operation based on effluent turbidity was the best for crushed quartz at 3.5 m/h and 8 m/h filtration rates without polymer. No conclusive effect of polymer addition on consistency of operation was observed. However, this may be the result of relatively poor mixing in the pilot plant.

Polymer addition did not significantly improve the filter performance at the filtration rates tested with the mixing provided in the pilot plant. However, the results may vary with further polymer mixing studies. Polymer addition reduced the FRL and WPC at low filtration rates but did not significantly affect the FRL and WPC at higher filtration rates. This may be due to the fact that better mixing (velocity gradient) is provided at high filtration rates resulting in more uniform polymer action. At low velocities, inadequate mixing may have caused localized particle agglomeration and subsequent clogging of filters. Factorial experimental analysis of the data suggested that the polymer addition between 0.02 mg/L and 0.1 mg/L had insignificant effects on the turbidity, FRL and WPC.

Results of the rate change tests suggest that crushed quartz provided substantially better resistance to turbidity increases during rate changes and recovers quicker than the other media types. Filter ripening sequence of crushed quartz is much better than the other media types with very low peak turbidities during ripening.

Acid solubility of all the media tested in this study were found to satisfy the standards. However, acid solubility of anthracite was more than that of rounded sand and crushed quartz. Scanning electron microscopic photographs of media surfaces generally indicated surface smoothing due to abrasion and deposition. No surface cracks were seen in crushed quartz. However, anthracite contained surface cracks due to abrasion. Particle deposit accumulations on the media surface relate to the lack of particle detachment efficiency during backwash. Long term accumulation of captured particles on the media surface is evident in the existing filter sand which was in service for seven years, approximately. Crushed quartz media surface did not change considerably and no particle accumulation was experienced during the test period. This indicates that efficient particle detachment during backwash can be achieved with crushed quartz. This filter media also has high abrasion resistance and can possibly retain its original shape during long term operations.

Crushed quartz media improved effluent quality more than the other media types tested but anthracite/sand dual-media provided longer FRL and higher WPC. However, the FRL and WPC of the crushed quartz are comparable to that of the existing filter media. For both crushed quartz and anthracite/sand dual-media, the best FRL, WPC and effluent turbidity were obtained at 8 m/h without polymer. Considering the facts: (i) that the goal was effluent quality improvement to <0.1 NTU; (ii) inefficiency of polymer addition at low filtration rates; (iii) abrasion resistance; (iv) resistance to sudden flow rate changes and; (v) filter ripening sequence, crushed quartz mono-media without any polymer addition may be the best alternative under the prevailing physical and operational conditions among those media tested in this study.

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Table 3.1 Summary of Pilot Plant Results

Flow Rate m/h	Poly. Dose mg/L	No. of runs	No. of Data	Filtrate Turbidity Min. NTU	Filtrate Turbidity Max. NTU	Filtrate Turbidity Mean NTU	Filtrate Turbidity skew.	Filtrate Turbidity **Stdv.	Influent Turb. NTU	WPC Mean m^3	FRL Mean h	FRL Range h
(a) Anthracite/sand dual-media												
3.5	0.00	16	7213	0.075	0.218	0.114	3.1	0.38	10.21±4.1	6.0	97.7	83 to 110
3.5	0.02	5	1387	0.089	0.099	0.093	8.6	0.05	8.98±2.5	5.5	89	89 to 89
3.5	0.10	4	788	0.083	0.102	0.090	0.2	0.09	12.16±3.4	4.0	65	65 to 65
8.0	0.00	12	8696	0.050	0.112	0.082	-0.2	0.33	10.60±3.1	14.0	98.8	92 to 108
8.0	0.06	13	2214	0.081	0.124	0.102	-0.1	0.12	10.56±3.2	2.7	19.1	11 to 34
12.5	0.00	14	2606	0.100	0.340	0.239	1.1	0.28	8.01±3.3	3.1	13.8	9 to 22*
12.5	0.02	3	445	0.293	0.540	0.387	0.7	0.19	8.98±2.5	2.7	12	10 to 15*
12.5	0.10	4	518	0.114	0.120	0.117	3.1	0.02	12.16±3.4	2.8	12.7	12 to 14
(b) Crushed quartz mono-media												
3.5	0.00	24	6752	0.037	0.069	0.052	9.8	0.23	10.21±4.1	2.3	37.3	23 to 50
3.5	0.02	4	935	0.046	0.060	0.052	7.0	0.14	8.98±2.5	1.9	30.3	21 to 40
3.5	0.10	4	727	0.062	0.079	0.069	1.7	0.12	12.16±3.4	1.4	22.3	20 to 25
8.0	0.00	7	3707	0.044	0.048	0.046	2.0	0.05	10.60±3.1	6.4	45.2	35 to 55
8.0	0.06	18	3385	0.058	0.087	0.071	-0.2	0.17	10.56±3.2	2.1	14.6	9 to 23
12.5	0.00	13	1653	0.052	0.176	0.094	4.4	0.37	8.01±3.3	1.8	8.1	3 to 14
12.5	0.02	3	320	0.066	0.076	0.071	2.6	0.08	8.98±2.5	1.6	7.4	6 to 8.3
12.5	0.10	6	456	0.064	0.142	0.106	1.5	1.29	12.16±3.4	1.5	6.6	4 to 9
(c) Existing filter mono-media												
3.5	0.00	17	5375	0.054	0.116	0.079	7.2	0.21	9.42±4.0	2.7	44.3	32 to 62
8.0	0.00	9	1703	0.103	0.209	0.143	2.4	0.21	10.56±3.2	2.3	16.6	11 to 23
12.5	0.00	6	518	0.150	0.406	0.250	1.8	0.29	12.16±3.4	1.5	6.8	4 to 10

* Cycle terminations were based on turbidity or headloss criterion. All other FRL values in Table 3.1 were dictated by the headloss criterion.

** standard deviation after transformation to normally distribute the observed data according to Equation 3.2.

Table 3.2 Factorial Experimental Design

X1(level) m/h	X2(level) mg/L	X3(level)	*TURB NTU	*WPC m^3	*FRL h
3.5 (-1)	0.02 (-1)	C (-1)	3.26	0.51	0.84
12.5 (+1)	0.02 (-1)	C (-1)	2.88	0.67	0.87
3.5 (-1)	0.10 (+1)	C (-1)	2.92	0.54	0.91
12.5 (+1)	0.10 (+1)	C (-1)	2.49	0.69	0.91
3.5 (-1)	0.02 (-1)	B (+1)	2.59	0.41	0.60
12.5 (+1)	0.02 (-1)	B (+1)	1.49	0.61	0.75
3.5 (-1)	0.10 (+1)	B (+1)	2.62	0.43	0.66
12.5 (+1)	0.10 (+1)	B (+1)	2.36	0.60	0.74

X1=Filtration Rate; X2 = Polymer Dose; X3= Media Type
* transformed data according to Eqs. 3.2, 3.3 and 3.4.

Table 3.3 *Effects of Factors and Interpretations

Parameter	Filt. rate (X1)	Poly. dose (X2)	Media type (X3]	Increased filtration rate	Increased polymer dose	Media type**
TURB	-0.54	0.05	-0.62	Increase	Insignificant	Increase(C < B)
FRL	0.17	0.02	-0.09	Decrease	Insignificant	Increase(C < B)
WPC	0.06	0.04	-0.20	Insignificant	Insignificant	Increase(C < B)

* From factorial analysis and half-normal plots
** C: Crushed quartz mono-media; B: Anthracite/sand dual-media
signs were reversed due to the negative transformation of turbidity data

Table 3.4 Results of Rate Change Tests

Filtration Rate			Polymer dose	Turbidity			Recovery time
From m/h	To m/h	Change %	mg/L	Initial NTU	Peak NTU	Change %	min
			(a) Anthracite/sand dual-media				
3.5	9.1	160	0.00	0.42	1.10	162	20
3.5	11.7	234	0.02	0.14	0.30	114	18
8.0	10.8	35	0.06	0.14	0.22	57	10
			(b) Crushed quartz mono-media				
3.5	14.3	309	0.00	0.42	0.60	43	18
8.0	9.8	23	0.06	0.11	0.12	5	6
			(c) Existing filter mono-media				
3.5	9.8	180	0.00	0.10	0.25	150	25
8.0	12.5	56	0.00	0.15	0.50	233	30

Influent Turbidity = 10.57±0.81 NTU

Table 3.5 Abrasion Resistance of Filter Media

Filter media	Acid solubility %	ES		UC		Friability after	
		Fresh mm	Used* mm	Fresh --	Used* --	375 rev. %	750 rev. %
Existing media	2.14	--	0.61	1.34		0.12	0.8
Crushed Quartz	0.22	0.5	0.56 (12)	1.52	1.38 (-9)	2.61	4.08
Round Sand	0.12	0.46	0.54 (17)	1.59	1.56 (-2)	1.07	1.98
Anthracite	0.97	0.89	0.94 (6)	1.55	1.44 (-7)	18.9	24.3

* values in parentheses indicate the percentage increase

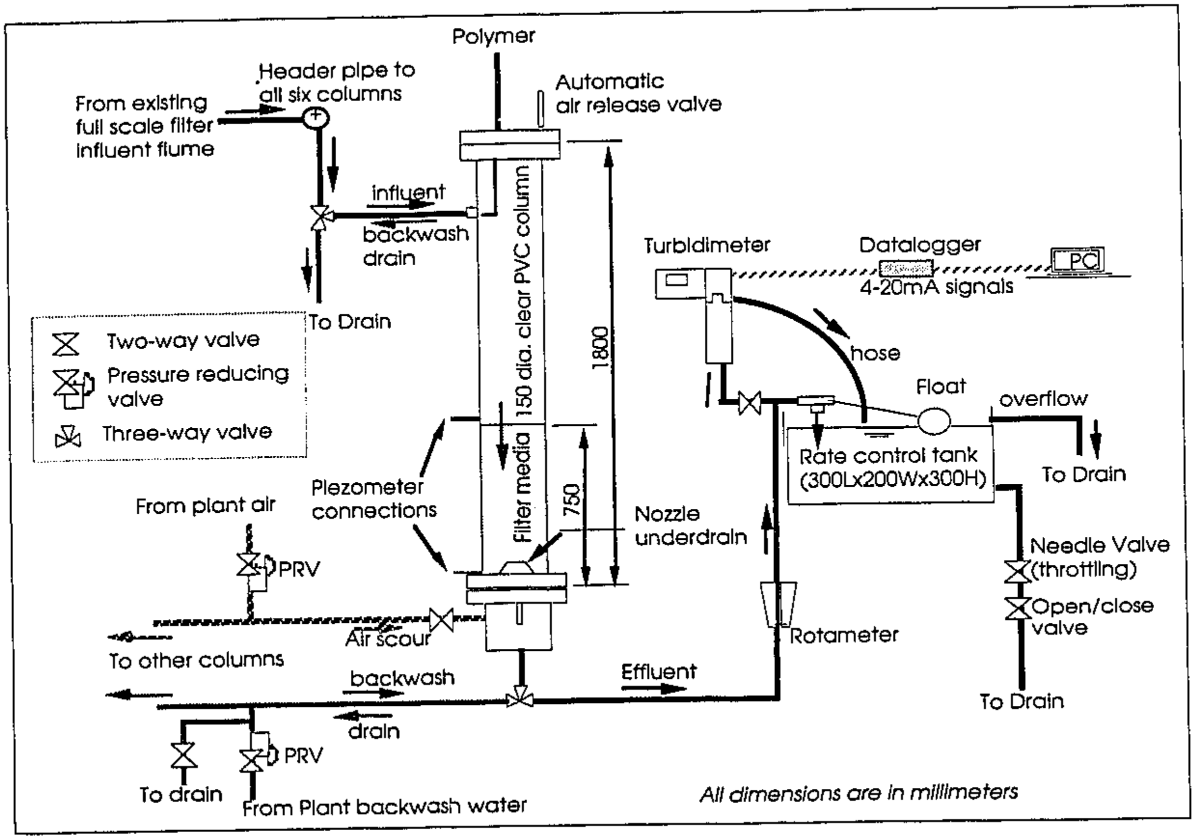

Figure 3.1 Filtration Pilot Plant (One of Six Columns Shown)

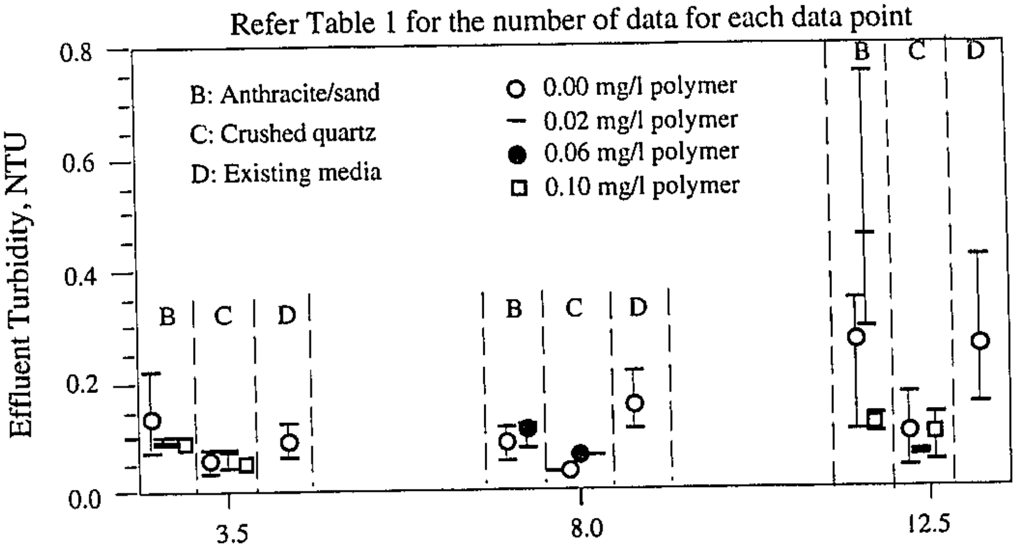

Figure 3.2 Comparison of Average Turbidity

(The bar indicates the range of data and the data point indicates the average value)

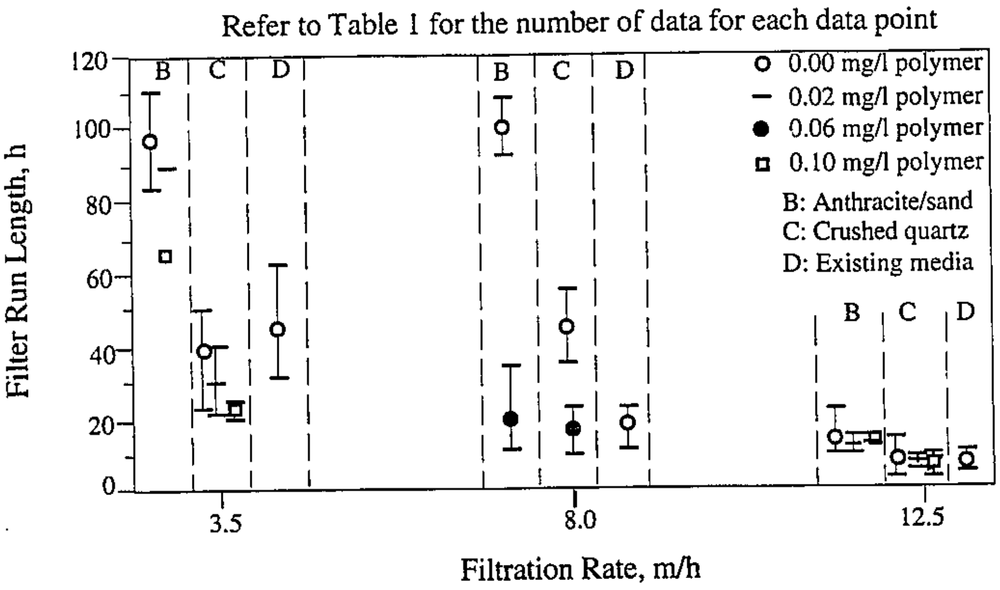

Figure 3.3 Comparison of Filter Run Length

(The bar indicates the range of data and the data point indicates the average value)

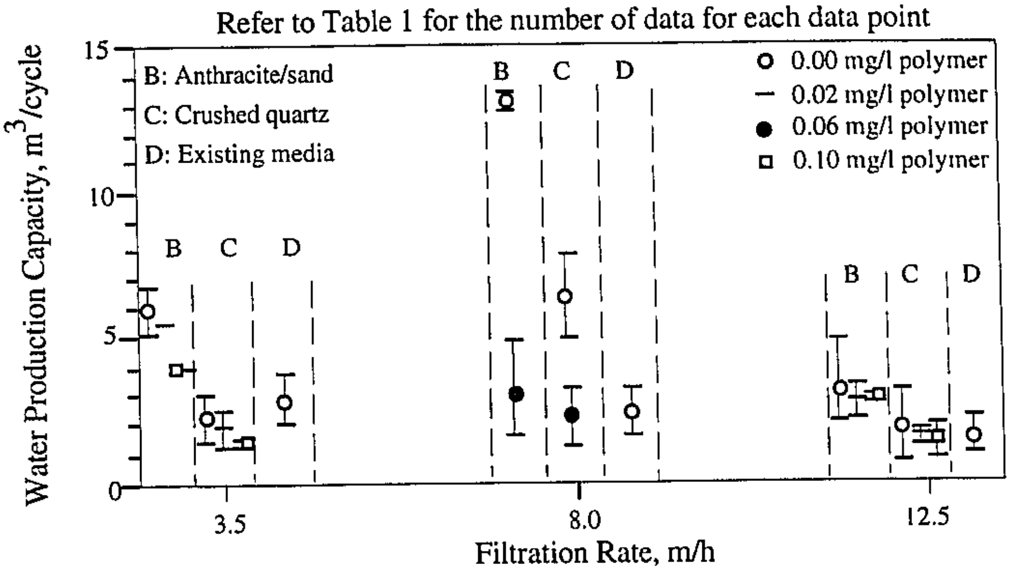

Figure 3.4 Comparison of Water Production Capacity

(The bar indicates the range of data and the data point indicates the average value)

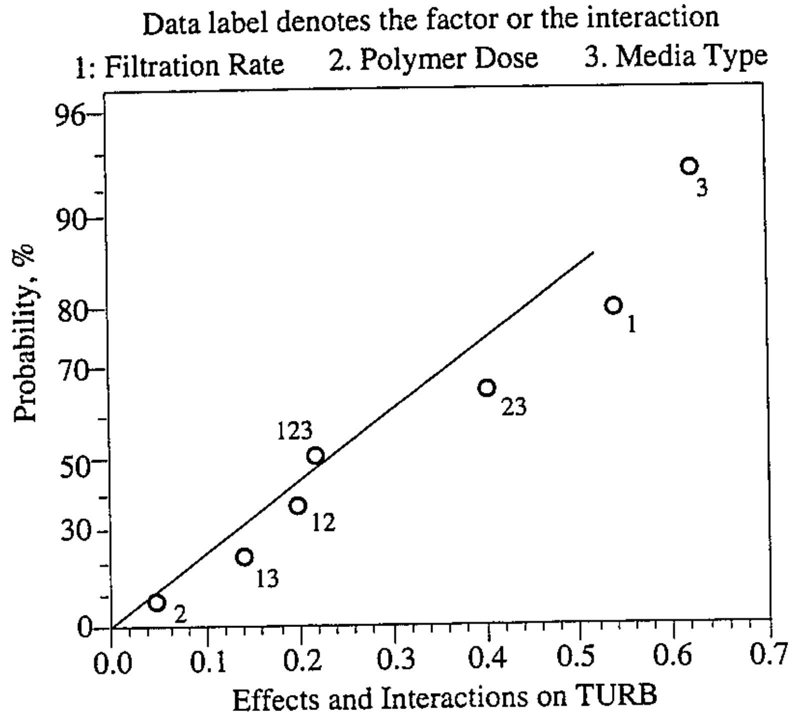

Figure 3.5a Half Normal Plot for TURB

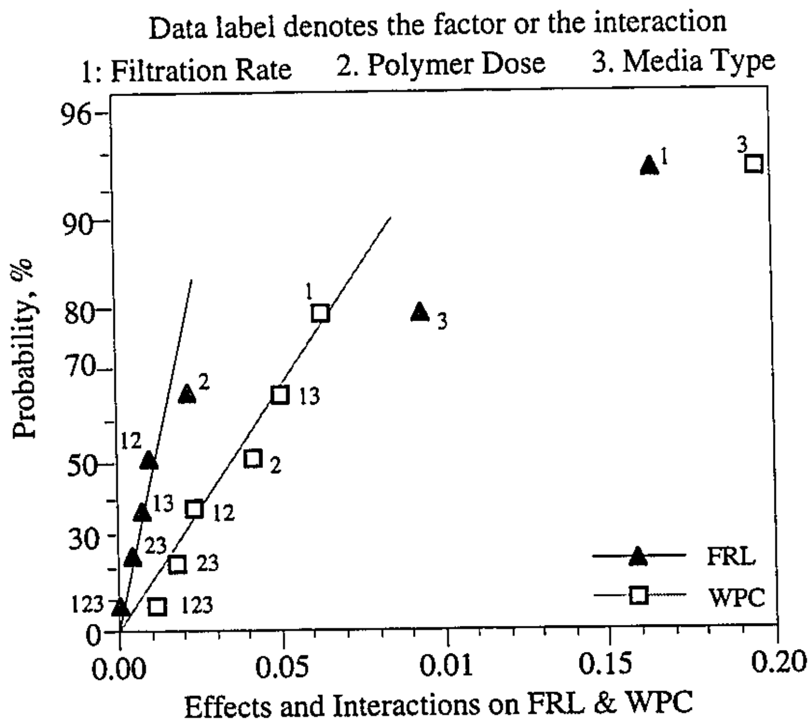

Figure 3.5b Half Normal Plots for FRL and WPC

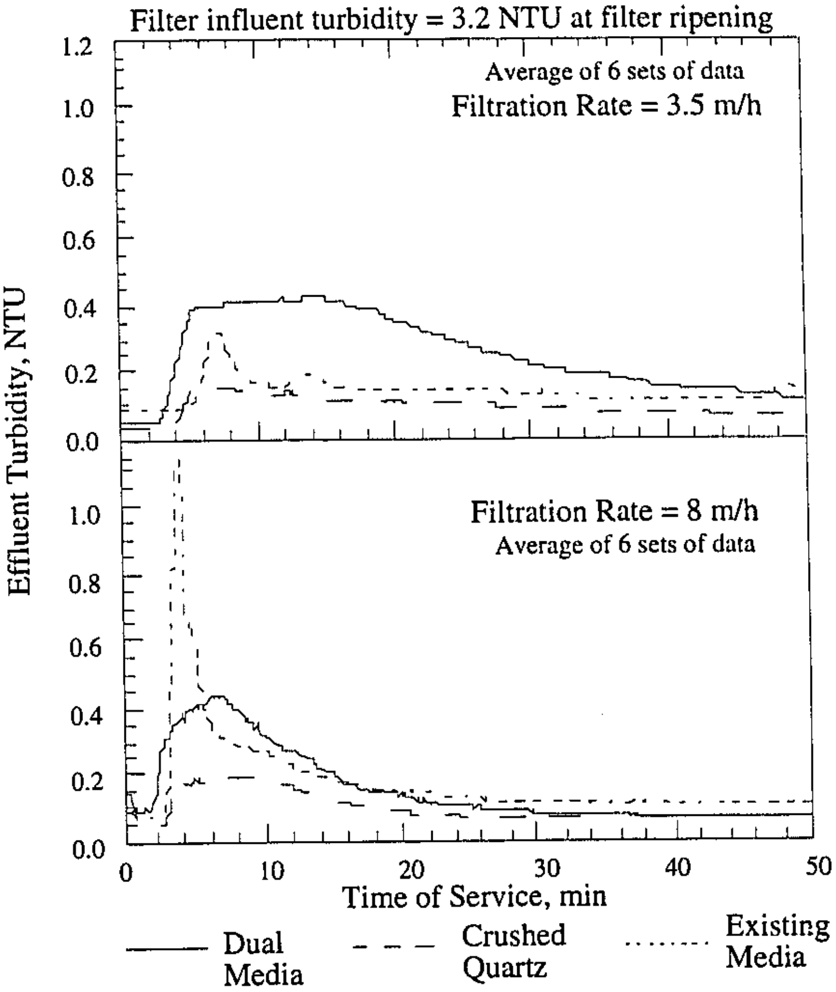

Figure 3.6 Comparison of Filter Ripening Sequence

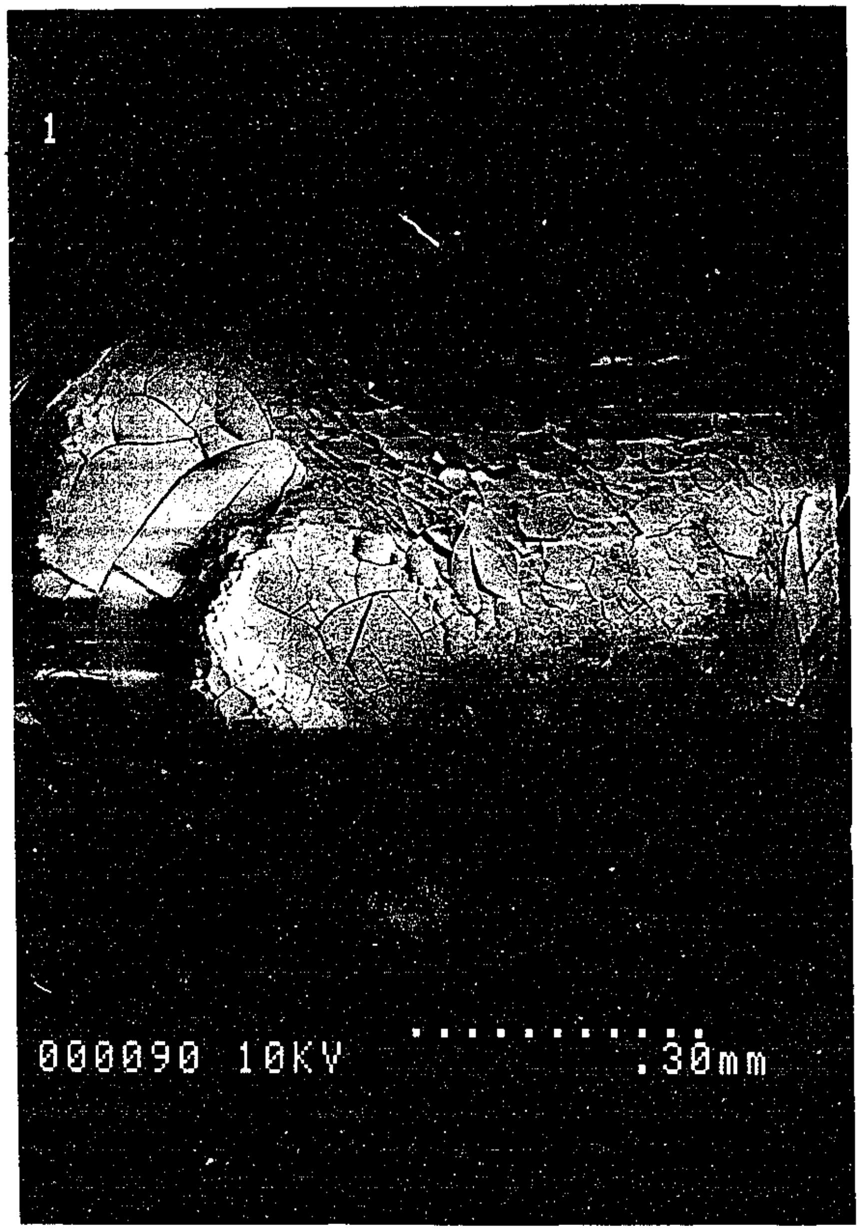

Figure 3.7a SEM Image of Existing Media (Used)

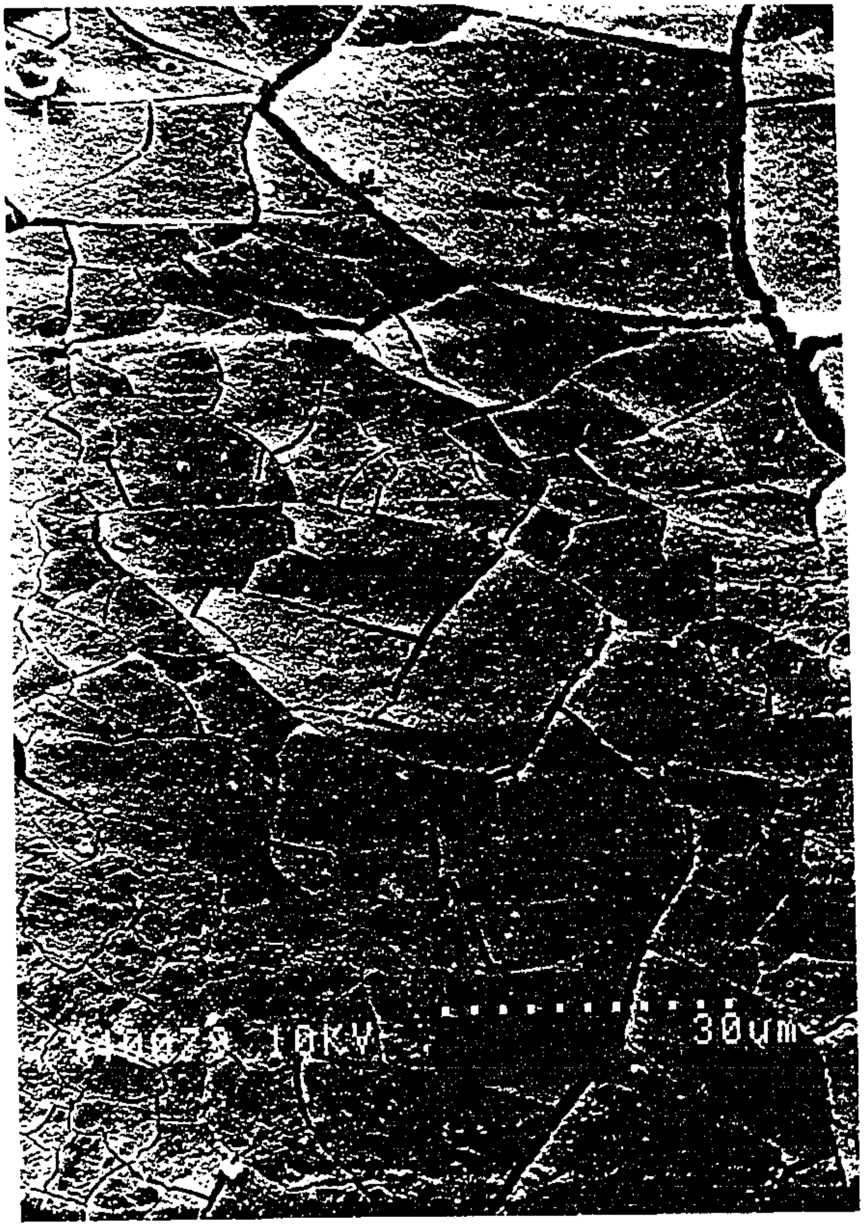

Figure 3.7b SEM Image of Existing Media (Used)

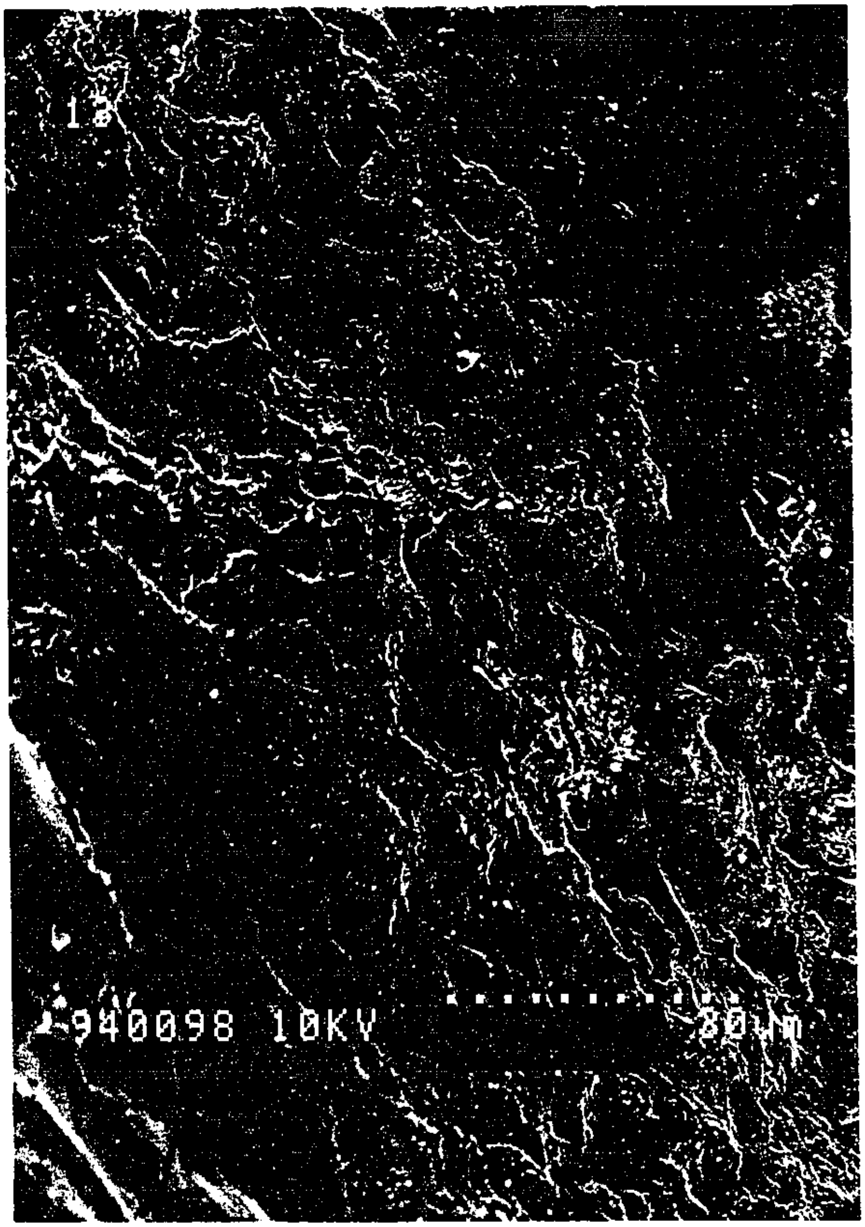

Figure 3.7c SEM Image of Existing Media (Acid-Washed)

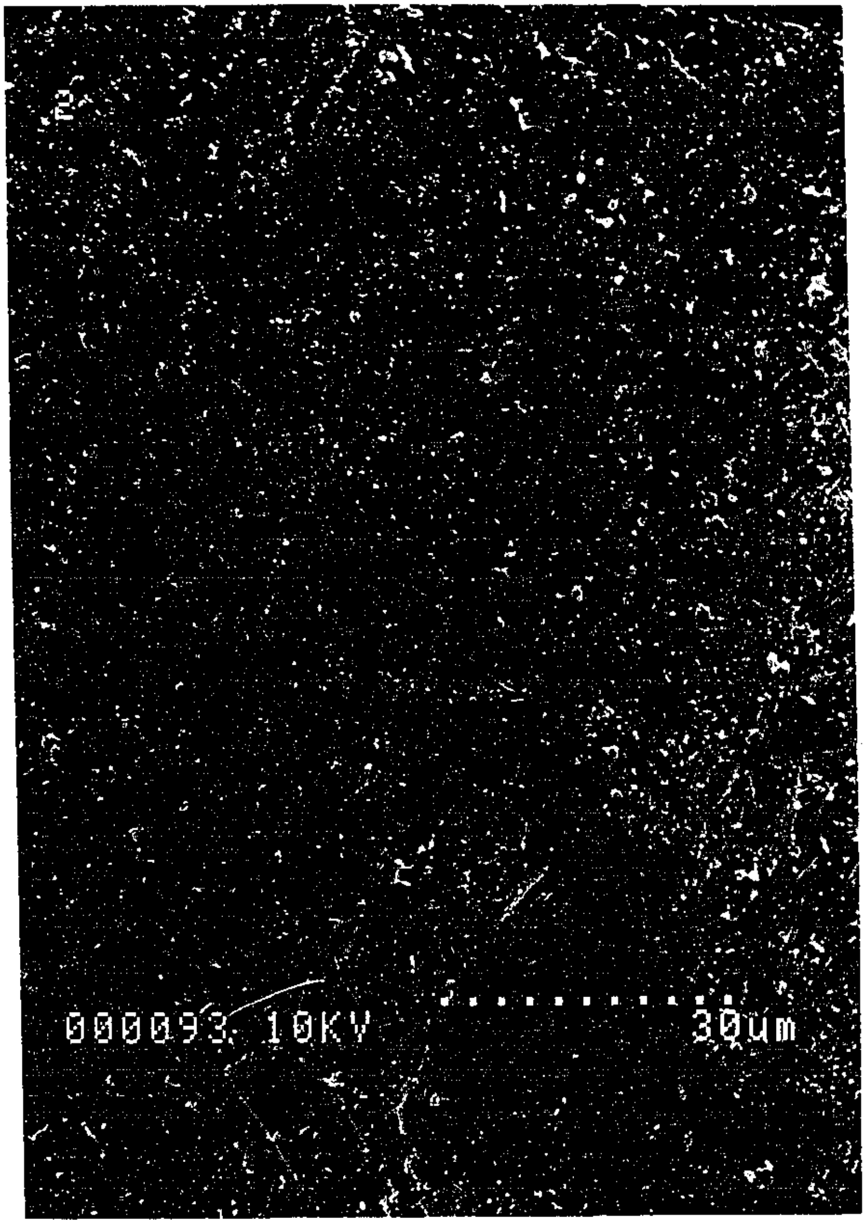

Figure 3.8a SEM Image of Crushed Quartz (Fresh Media)

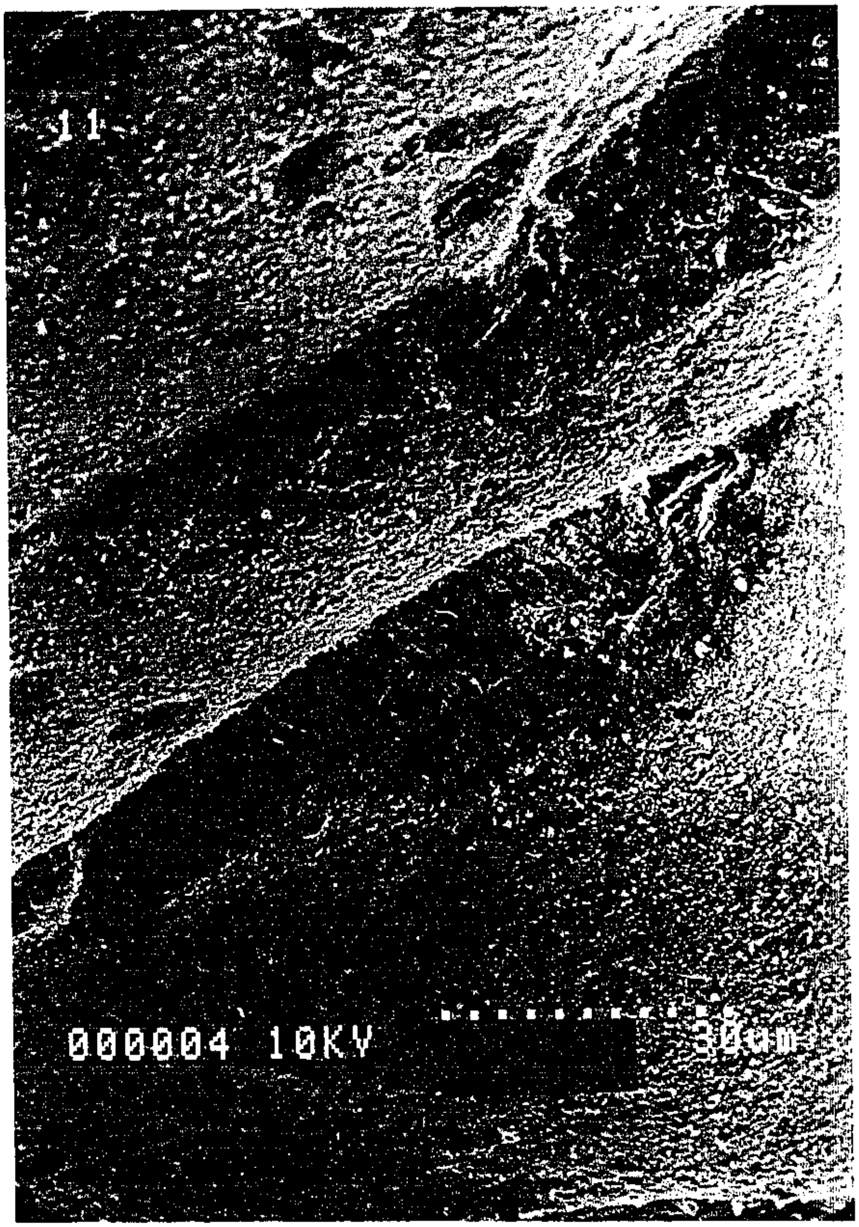

Figure 3.8b SEM Image of Crushed Quartz (Used media)

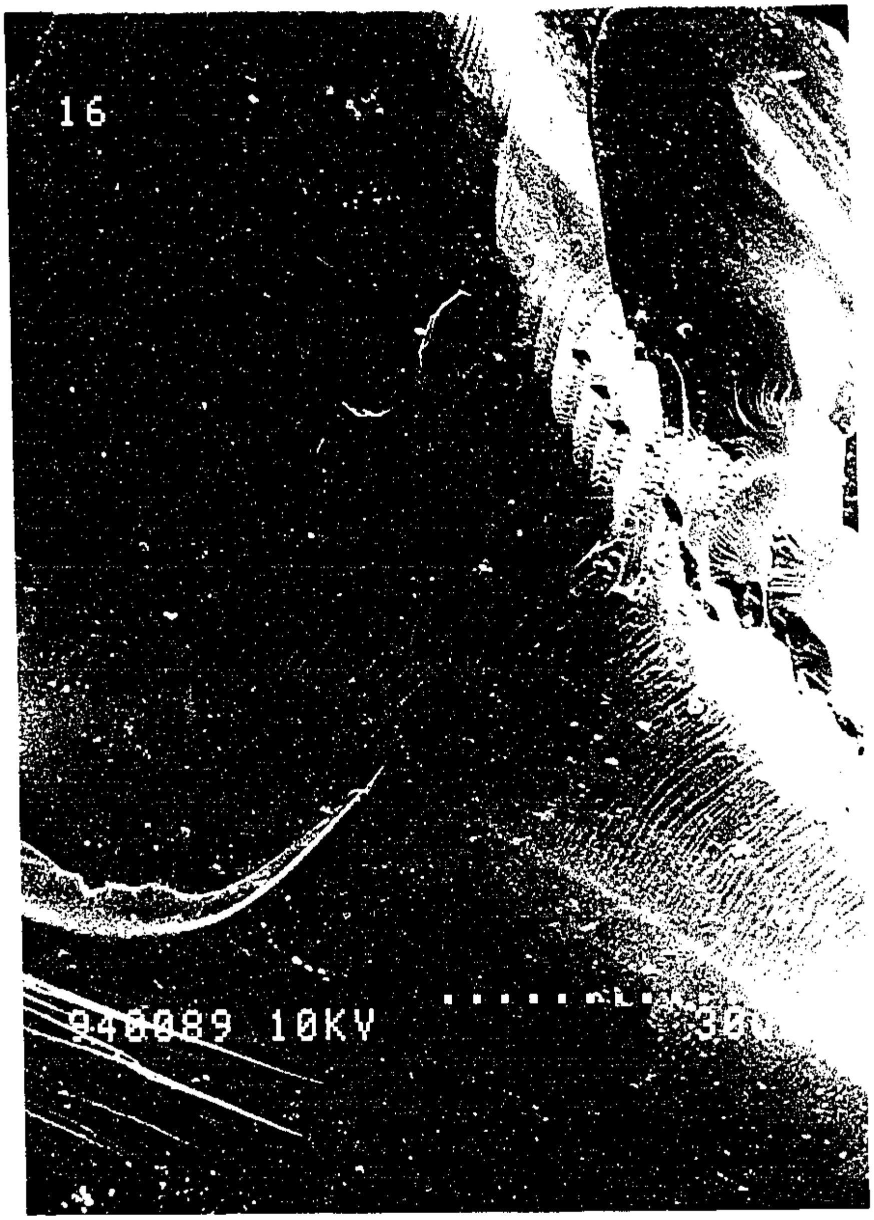

Figure 3.8c SEM Image of Crushed Quartz (Acid-Washed Media)

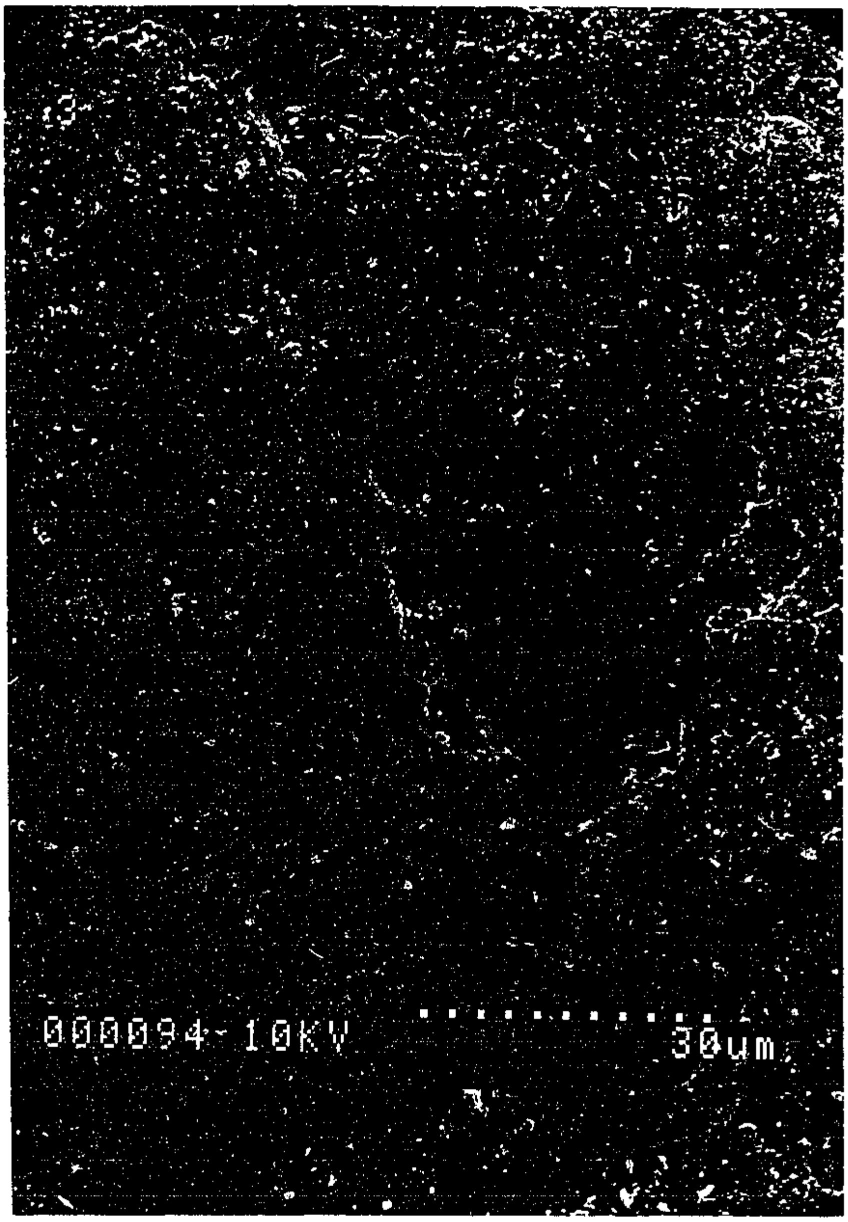

Figure 3.9a SEM Image of Round sand (Fresh Media)

Figure 3.9b SEM Image of Round sand (Used media)

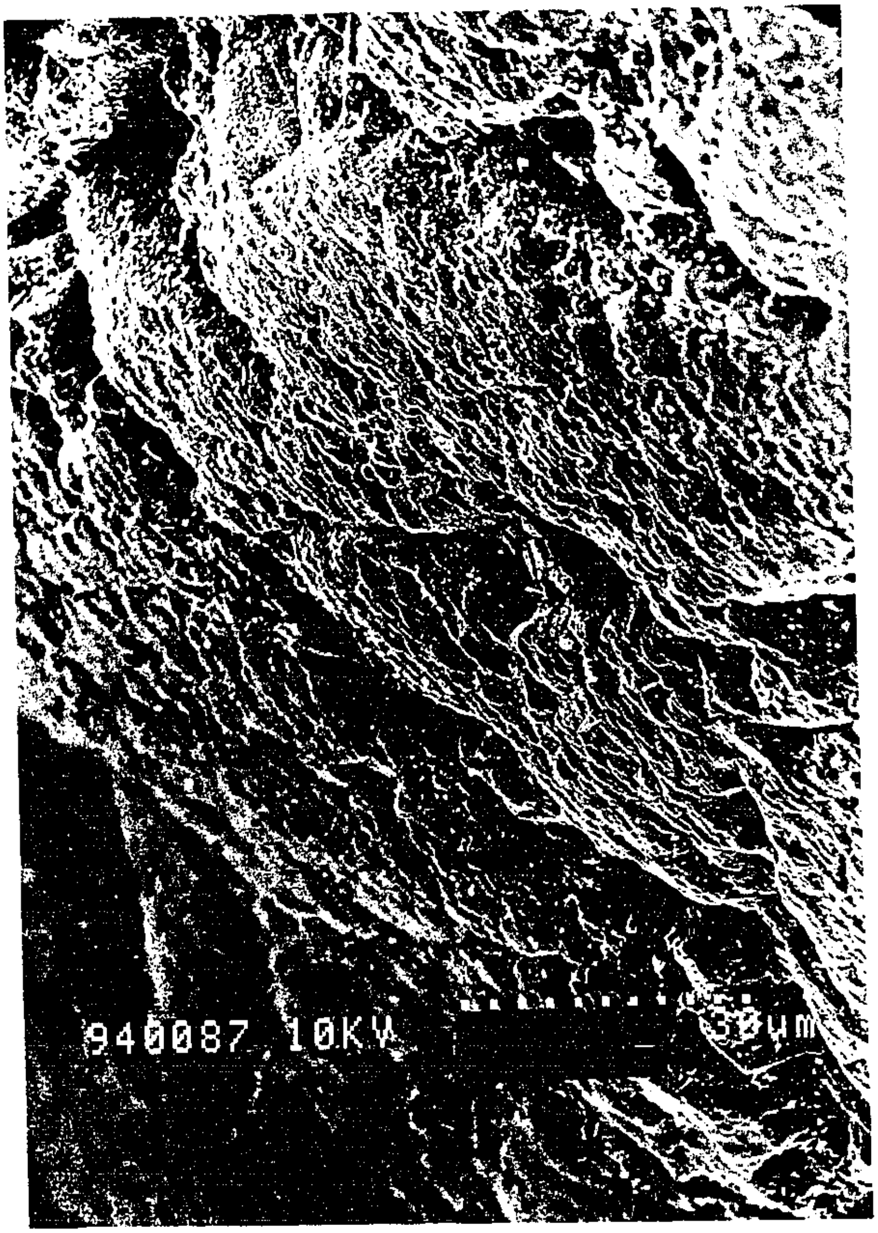

Figure 3.9c SEM Image of Round sand (Acid-Washed Media)

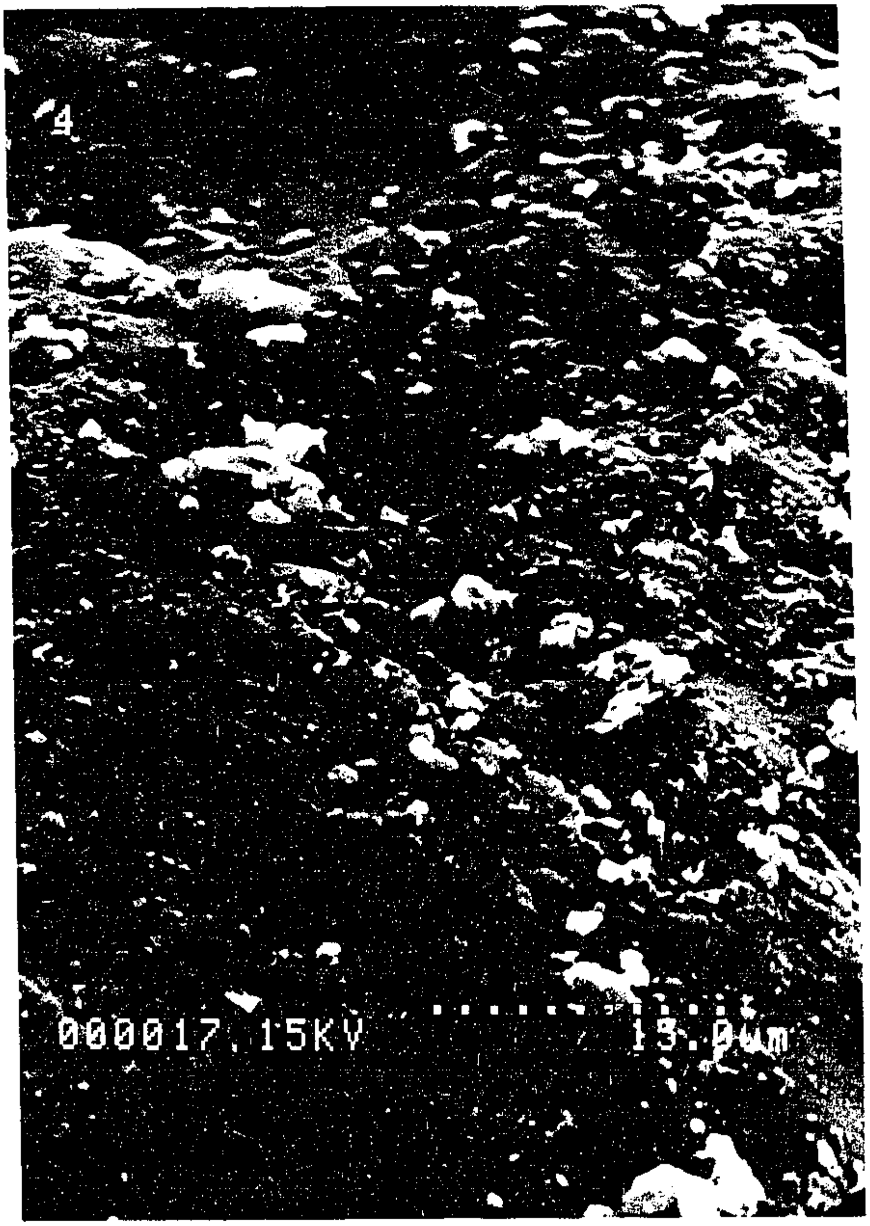

Figure 3.10a SEM Image of Anthracite (Fresh Media)

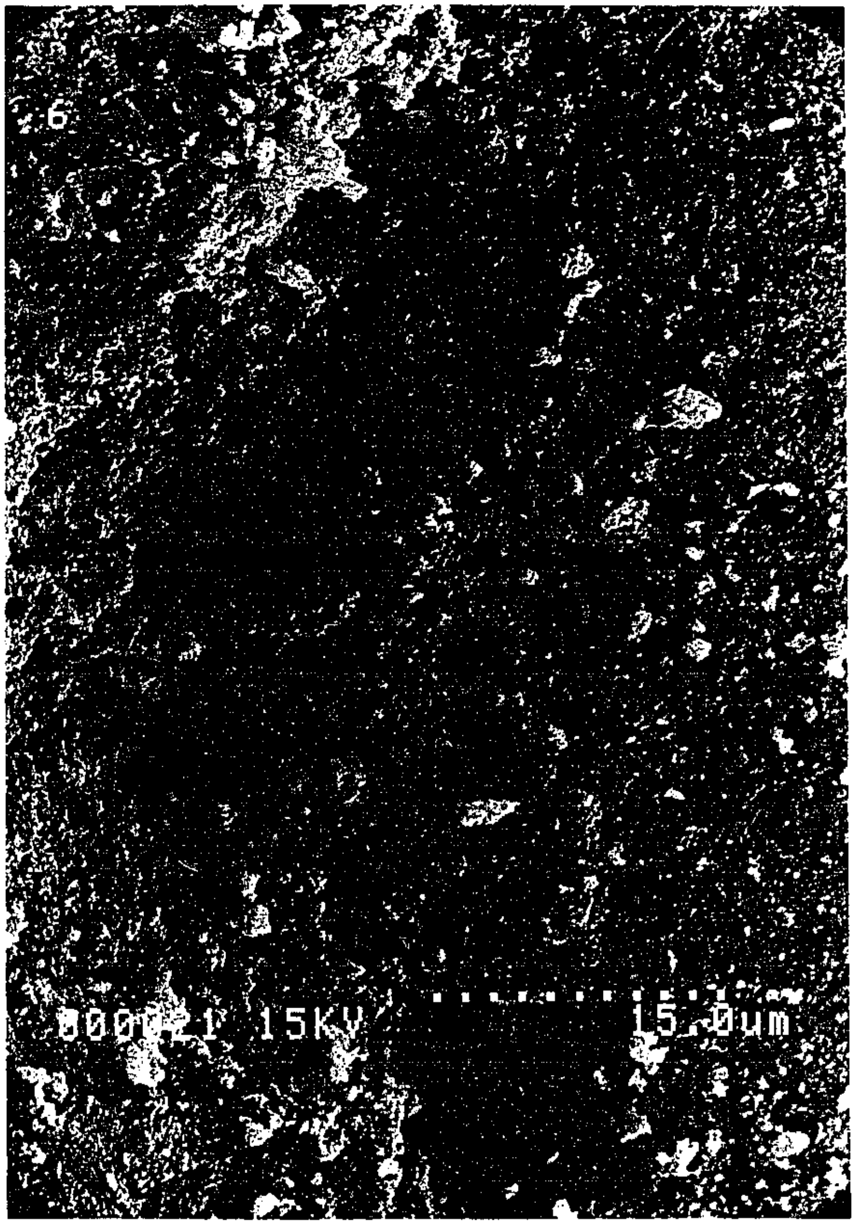

Figure 3.10b SEM Image of Anthracite (Used media)

Figure 3.10c SEM Image of Anthracite (Acid-Washed Media)

Chapter 4

Statistical Data Evaluation and Reliability-based Design for Water Filtration

4.1 Introduction

For the design of unit processes in water and wastewater treatment, statistical concepts are often used for the selection of design criteria that will ensure compliance with a guideline at some level of reliability. However, most common techniques used for the analysis of variance and multiple regression analysis are justified by assuming homogeneity of error variance, independence of observations and normality of observations (Box and Cox, 1964). In practice however, the data distributions obtained from unit processes may be non-normal due to numerous reasons and, in regression, outliers may contribute to non-normality of the distribution.

For example, values higher than average filtrate turbidity are expected during filter ripening when poor quality initial effluent is released (Amirtharajah and Wetstein, 1987). Higher turbidity is also expected to occur during turbidity breakthrough when the filter becomes exhausted. These phenomena can cause non-normality, usually a positive skewness to the effluent turbidity distribution. Since a large part of statistical theory (such as testing hypotheses) is built on the assumption that the data are normally distributed, the normality of the observed data must be verified. Non-normal data must be transformed to normality, therefore, normal statistical concepts can be used to evaluate the filtration data and to assess the filter performance.

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Understanding the association of turbidity with possible adverse effects in drinking water, has prompted the implementation of progressively more stringent turbidity guidelines for drinking water. The importance of the reliability, or consistency, in the production of high quality drinking water has prompted many regulatory agencies not only to specify a numerical limit but also to specify percentage of operating time that the turbidity shall be less than the limit. In the Unites States, the finished water turbidity must be less than 0.5 NTU, 95% of the time (USEPA, 1989, 0.2 NTU, if the raw water turbidity is less than 1 NTU) to obtain maximum removal credits for pathogens. The guidelines for Canadian Drinking Water Quality (1993) state that the effluent turbidity should be less than 1 NTU for 95% of the filter operating time. As a result of the increasingly stringent guidelines and the requirement to consider reliability in meeting the guidelines, it has now become necessary to take more refined approach in the assessment and design of the filtration process.

Normally, two approaches or a combination of both are used in filter design. The first is a procedure based on the hydraulics of filtration such as allowable headloss across the filter. This requires the knowledge of the hydraulic characteristics of the filter media. Effluent quality can be obtained from mathematical models based on pre-established model constants for filter media (Ives, 1982). However, individual plant operating conditions and influent water quality may vary and the use of model constants established from a different operating condition may not lead to a good design. As a result, pilot-scale tests are often used in design and optimization of the filtration process as they can better represent plant operating conditions. Even with the use of pilot plants, given the stringent standard, it is important that the pilot-scale tests are operated appropriately and results are analyzed and interpreted properly to ensure a successful design.

In terms of proper operation of the pilot-scale facility, it must be recognized that the performance is influenced by many operational factors such as influent quality, temperature, the use of polymer as filter aid and backwashing procedures. Factors such as influent turbidity can vary dramatically. In addition, filter operating strategies may also vary seasonally. Such variations often cause filter performance to be inconsistent. In pilot-scale filtration strategies, it is therefore required to operate for a reasonably long time to accommodate variations in influent quality.

The need to consider reliability, or consistency in filtration performance requires the need to statistically analyze results from pilot-scale tests. For normally distributed data, performance and consistency of filter effluent are easily described by the mean and standard deviation (σ) or the variance (σ^2), respectively. However, if the data distribution is non-normal, which is the case for filtration data, transformations to normality are required to assess performance and consistency. With these transformations, the consistency can be well defined allowing a coefficient of reliability (COR) to be incorporated into the design to account for variations in pilot plant operating and performance conditions. Knowledge of variations and these statistics will also allow data obtained from short-term pilot-scale tests to be assessed in terms of reliability. This can result in the study of more variables and alternatives, as it allows pilot filter runs to be for a shorter time period.

Reliability can be obtained for many types of data distributions such as normal, log-normal, gamma, exponential and Weibull (Hahn and Shapiro, 1967). Tchebycheff inequality may be used to estimate the reliability when little is known about the distribution other than the mean and standard deviation (Amstadster, 1971). However, it is important to identify the data distribution before estimating the reliability of operations. Niku et al. (1979) characterized activated sludge plant performance (effluent BOD and

SS) by a log-normal distribution and estimated COR based on log-normal distribution for design purposes. Kobylinski et al. (1993) expressed the design long-term average of stream pollutant concentrations in terms of allowable waste load using a log-normal distribution.

This chapter describes a data collection procedure using a filtration pilot plant, the statistical evaluations such as the tests for distributional assumptions, and the method for finding a suitable transformation to achieve normally distributed data. Based on the transformed normal data, the reliability of filter operations was established and a rational design procedure was formulated. The factors influencing the COR were also examined. The rational design procedure relates the design effluent turbidity to the regulatory standards on a long-term basis. In addition, the robustness of the t-test was investigated using the non-normal data from the pilot plant.

4.2 Background

Presented in this chapter is a part of the study which evaluated filter media aspect of an upgrading of existing filters at the Rossdale Water Treatment Plant in Edmonton, Alberta, Canada to meet new more stringent guidelines. A pilot plant filter study was conducted to provide guidance toward achieving the above goal. A previous study was completed involving screening tests on a number of different types of media (Suthaker et al. 1995a). Based on the results and recommendations, the use of crushed quartz filter media or the use of anthracite/rounded sand dual-media were found to be capable of improving filter performance. Further experiments were required to choose one of the above filter media for the use in full scale filters. As a result, a subsequent study was conducted on the performance of these two types of media at different filtration rates

(Suthaker et al. 1995b). Statistical concepts were used to evaluate the filter performance based on effluent turbidity, Filter Run Length and Water Production Capacity.

4.3 Pilot Plant Data Collection Program

Six clear PVC columns of 150 mm diameter were used as the filters. The filters were operated at constant rate. A polymer feed system was installed with a multi-tube peristaltic pump. Polymer was injected into the feed pipes to the column against the flow. Filtered water turbidity was measured by 'flow-through' low range turbidimeters (Hach® model no. 1720C) and 4 to 20 mA outputs from the turbidimeters were recorded by a datalogger every 5 minutes. Filter run length (FRL) was determined as the time for the headloss across the filter bed reaches 1 m (dictated by plant conditions) or effluent turbidity (TURB) reaches 1 NTU, whichever occurred first. Most of the runs in this study were limited by the headloss criterion. Water produced during a filter run was reported as water production capacity (WPC). TURB, FRL and WPC were used to characterize the filter performance. The pilot plant was operated for different conditions each containing multiple filter runs as summarized in Table 4.1.

4.4 Tests For Distributional Assumptions

A statistical test of a distributional assumption provides an objective technique for assessing whether an assumed model provides an adequate description of observed data at a specified significance level. While this procedure permits the rejection of a model as inadequate, it does not prove that the model is correct. Some available tests for normality of the data and homogeneity of variance used in this study are presented hereafter.

4.4.1 Tests for normality

The normality assumption in practice simply requires that the filtration data (TURB, FRL, WPC) distribution be sufficiently close to a normal density. The normal probability plot can be used to graphically determine the normality of the data. Early tests such as Pearson's test (α_1 and β_2-statistics) and Fisher's test (g_1 and g_2-statistics) were based on the agreement between the observed and normal distributions with respect to the symmetry (Pearson's α_1, Fisher's g_1) and kurtosis (Pearson's β_2, Fisher's g_2) (Johnson, 1949). Anscombe and Tukey (1963) presented a method based on shape coefficients analogous to Fisher's g-statistics to assess the normality based on the examination of residuals. The Shapiro-Wilk test, also called as W-test, is an effective procedure for evaluating the assumption of normality against a wide spectrum of non-normal alternatives, even if only small number of observations (≤ 50) are available (Hahn and Shapiro, 1967; Shapiro and Wilk, 1965). The W-test has been shown to be more powerful than the regular chi-squared goodness of fit test. When a large number of observations are available (>50), D'Agostino's test becomes useful because of its simplicity and the ability to handle symmetric long-tailed alternatives (Hahn and Shapiro, 1967). Kolmogorov-Smirnov (K-S) test is popular partly because it can be used to compare sample distributions to any continuous type theoretical distribution (Kotz and Johnson, 1983). It is based on the goodness of fit of the observed and theoretical cumulative probability density function. A survey of techniques of normality tests is available (Hoaglin et al. 1985; Kotz and Johnson, 1983; Mardia, 1980). Pearson's test (α_1 and β_2-statistics) and Shapiro-Wilk test (W-statistics) were used to test the normality of the distribution in this study.

4.4.2 Tests for homogeneous variances

One of the assumptions made in the analysis of variance is that the variances are homogeneous. Several test procedures for comparing multiple variances are discussed in Kotz and Johnson (1983) and Jobson (1991). Hartley's test, based on the ratio of the maximum and minimum variances, is applicable when the sample sizes are equal (Neter et al. 1990). Bartlett's test (Neter et al. 1990) uses the chi-squared distribution and Cochran's test (Jobson, 1991) uses the ratio of maximum variance and the sum of variances. The above tests are extremely sensitive to non-normality of the data. To overcome such discrepancy, non-parametric tests such as Levene's test and Jackknife method (Kotz and Johnson, 1983) may be used. Bartlett's test and Levene's test were used to test the homogeneity of variances in this study. Though Bartlett's test is sensitive to non-normality, it is expected to produce reliable results for normally distributed transformed data.

4.5 Data Transformation Procedure

In practice, lack of normality is often associated with heterogeneous variances (Neter et al. 1990). Even if normality of distributions or homogeneity of variances could not be achieved, it is always preferable to transform the data to minimize the deviations from normality or minimize the heterogeneity of variances (Box and Cox, 1964). Figure 4.1 depicts some normal probability plots of TURB in this study. A normally distributed data set will fall on a straight line in a normal probability plot. Figure 4.1 suggests the non-normality of the filtrate turbidity data. A power transformation ($x' = x^{\lambda}$, where x is the observed data, and x' is the transformed data) of the observed data may satisfy the full normal theory assumptions, i.e., the observations are independently normally distributed with constant variance (Box et al. 1978, Box and Cox, 1964). A special case of the above transformation is when $\lambda = 0$, the transformation becomes $x' = \log(x)$ denoting a log-normal distribution of the observed data.

However, there is no guarantee that the solution will result in an acceptable normal-like distribution. Therefore, the distribution of the transformed data should also be carefully studied (Jobson, 1991). A common trial and error approach with several values of λ was used to check the validity of the distributional assumption. Box and Cox (1964) emphasized that the λ for transformation represents a compromise and different values of λ may be needed to satisfy different distributional assumptions such as normality and homogeneity of variances. Therefore, many transformations in the vicinity of the outcome (λ) of Box-Cox transformation were performed to establish the range of λ that satisfies the normality and constant variance assumptions. From this range of λ, the best transformation to satisfy the above assumptions can be selected.

4.6 Results And Discussion

4.6.1 Box-Cox transformation

For transformation to stabilize the variances, the usual method is to determine the relationship between the observed standard deviations and means, empirically or theoretically (Bartlett, 1947). Box and Cox (1964) suggested a transformation of the dependent variable x ($x > 0$) to x' in the form of:

$$x' = \frac{x^{(\lambda)} - 1}{\lambda} \quad \text{when } \lambda \neq 0 \qquad [4.1]$$

and

$$x' = \log(x) \quad \text{when } \lambda = 0 \qquad [4.2]$$

Since the analysis of variance is unchanged by a linear transformation, Equation 4.1 can be written as:

$$x' = x^{(\lambda)}, \quad \text{when } \lambda \neq 0 \qquad [4.3]$$

Special cases of λ have been identified as reciprocal (for λ=-1), reciprocal square root (for λ=-0.5) square root (for λ=0.5) and log (for λ=0) transformations (Box et al. 1978). Box et al. (1978) suggested to plot the graph of standard deviation (σ) Vs mean (μ) and to fit the Equation 4.4 to the data to estimate λ.

$$\sigma = k \bullet \mu^{(1-\lambda)} \qquad [4.4]$$

Figure 4.2a, 4.2b and 4.2c depict the correlation between σ and μ of the TURB, FRL and WPC, respectively. When λ = 1, no variance stabilizing transformation is required as Equation 4.4 becomes $\sigma = k$, constant, independent of μ. Regression techniques were used to estimate λ by fitting a curve in the form of Equation 4.4. Table 4.2 summarizes the estimated coefficients (λ) and regression outputs. Table 4.2 suggests that the σ is more correlated with μ for TURB indicating distant association to normality, and lesser for FRL and WPC. Since heterogeneity of variances is related to non-normality of the data, the transformation in the vicinity of λ may satisfy the requirements of normality and variance homogeneity. For each λ, the normality tests (Pearson's and Shapiro-Wilk's) and tests for homogeneity of variances (Bartlett's and Levene's) were done. Acceptance ranges of λ were established for each test where λ satisfies the test requirements.

4.6.2 Universality of transformation for filtration data

Some treatment plants use polymer as filter aid. In addition, the filter media used may vary from plant to plant. In this study, performance of three different filter media and the effects of polymer addition were evaluated in a comprehensive manner containing large number of filter runs to accommodate influent quality variation expected in a plant. This would facilitate the investigation of the required individual transformation to normality and homogeneity of variances for each experimental condition and hence the universality of the transformation for filtration data. Universality of the filtration data transformation in such instances is of concern, as the transformations obtained from this study could be applied to all constant rate filtration plants. Therefore, the data was grouped into various subdivisions as indicated in Tables 4.3a, 4.3b and 4.4. One set contained the whole data as a group (case 1 of all media types, Tables 4.3a, 4.3b and 4.4) and subgroups. The acceptance ranges of λ for Pearson's test (α_1 and β_2-statistics) and Shapiro-Wilk test (W-statistics) were established where the distribution is expected to be normal (Tables 4.3a and 4.3b). The Bartlett's test and Levene's test were also performed on the observed and transformed data and respective acceptance ranges of homogeneous variances were established (Table 4.4).

4.6.3 Appropriate transformation

Lilliefors (1967) showed that in testing for normality when population mean and variance are estimated from the sample, the tabular values of a test statistic are too conservative. The test statistics and the acceptance ranges found in this study for a normal distribution do not restrict the transformations to a specific value but suggest the validity in the vicinity of the acceptance range of λ (Kelker, 1994). A careful look at Tables 4.3a, 4.3b and 4.4 suggests that a single transformation for each TURB, FRL and WPC can satisfy all or most of the normality and variance tests for the subgroups of data.

In addition, the transformations were graphically evaluated (Figures 4.3a, 4.3b and 4.3c) to check whether different transformations were required for different subgroups of data. The correlation coefficients were less than 0.46 for linear, polynomial and logarithmic functions when fitted to the data. There was no evidence of internal correlation of transformations and a unique transformation is acceptable for all subdivisions. In order to obtain a unique transformation, a transformation that satisfies most of the tests (homogeneous variances, normality) need to be identified. The λ, where most of the tests were satisfied, was chosen by trial and error as the appropriate λ for transforming the observed data to normal distribution and to have homogeneous variances. The respective best transformation is generally expected to be near those λ values. On the basis of the above analysis, the appropriate values are $\lambda = -0.4$ for TURB, $\lambda = -0.2$ for FRL and $\lambda = -0.3$ for WPC, as defined by Equation 4.3. Therefore,

$$x'_{TURB} = x_{TURB}^{(-0.4)} \qquad [4.5]$$

$$x'_{FRL} = x_{FRL}^{(-0.2)} \qquad [4.6]$$

$$x'_{WPC} = x_{WPC}^{(-0.3)} \qquad [4.7]$$

Table 4.5 summarizes the transformed data and some of its statistical parameters according to Equations 5, 6 and 7. It should be noted that the λ for the best transformation for TURB is the same as the obtained from Box-Cox's approach (Table 4.2). However, this is not true for FRL and WPC (Equation 4.6 and 4.7, Table 4.2). Lack of correlation of σ and μ for the observed FRL and WPC (more variance homogeneity of the observed data) undermine the estimation of λ by the Box-Cox's approach. This suggests that the normality and homogeneity of variances need to be examined for many λ's in the vicinity of that obtained by Box-Cox's approach, where less σ-μ correlation is evident.

4.6.4 Effect of Normality on Paired Comparison

In order to study the variation of filter performance with the filtration rate, polymer dose and media type, we need to compare the observed results in pairs at a time. Long term observations and minor influent quality variations in a pilot plant study cause variations about their respective average. When comparing two parameters showing such variations, making conclusions based on simple numerical comparisons alone may not be adequate. It requires the use of some statistical concepts such as t-test or non-parametric tests which are robust to non-normality of data. Despite the robustness, the statistical inferences from t-test results changed with the normality of the data. The significance level and the statistical inferences of some comparisons of the non-normal observed data (Table 4.1) were different from that of the normal transformed data (Table 4.5). Table 4.6 shows such differences in the statistical inferences when performed with the observed data and with the transformed data by comparing two observations by t-test (at 95% confidence level). For example, when the effect of media type on TURB is considered at 12.5 m/h with no polymer addition, the statistical inference from the t-test on the non-normal observed data are "$TURB_B > TURB_D > TURB_C$" (significance level (α) of 0.017). However, after transformation to normality, the statistical inference changed to "$TURB_B > TURB_C$ and $TURB_D > TURB_C$" ($\alpha = 0.001$). For the inference of "$TURB_B > TURB_D$", α increased to 0.457 (the statistical inferences based on the transformed data were not sensitive to small variations in λ). This may be due to severe non-normality of the filtrate turbidity data. Such variations are expected as the tests of significance become more valid and sensitive when the sampling distribution is normalized (Johnson, 1949). Therefore appropriate transformations to normality are required before making statistically correct inferences about the filter performance. Such inferences were used to make conclusion about filter performance (Suthaker et al. 1995a, 1995b).

4.7 Reliability Of Filtration Data

Reliability in general terms is defined as the probability that a device will perform its intended function for a specified time, under specified conditions. Reliability is a probability of success. A widely accepted definition reads "reliability is the probability of a device performing its purpose adequately for a period of intended time under the operating conditions encountered (Bazovsky, 1961). The use of reliability in filtration is very applicable since filter performance often varies according to fluctuations encountered in the operating conditions of a filtration plant. In addition, filters are expected to operate for a specified time (design FRL) with turbidity under a limiting standard (regulatory and in-plant guidelines) which require consideration of reliability. In reliability-based design and testing, reliability and confidence levels are used in a combined manner (Niku et al. 1979, Bae and Ichikawa, 1993).

The probability of failure depends on the distribution function of the variable of interest. The simplest distribution to express the reliability in terms of confidence level ($1-\alpha$, expressed as percentage) is the normal distribution. However, many other distributions such as log-normal, Weibull, exponential, etc., have been used to estimate the reliability (Chorafas, 1960; Hahn and Shapiro, 1967; Benjamin and Cornell, 1970). Identification of the observed data distribution is important to estimate reliability. Since the filtration data were shown to become normally distributed by appropriately transforming the observed data (Equations 5, 6 and 7), reliability estimation based on the normal distribution is possible for the transformed filtration data.

4.7.1 Estimation of Reliability

When the monitoring parameters exceed the criterion for the termination of a filter run, it can be considered as the failure of filter operation. Such criteria occur when (i) the turbidity exceeding a specified value (X_s), (ii) the headloss across the filter bed exceeds the allowable limit, and (iii) the time limit of FRL is reached. Criterion (ii) is fixed by the physical limitations of the design and (iii) is determined by individual plant operators. Since effluent turbidity standards recommend percentage of compliance, it can be translated into reliability of filtration with respect to effluent turbidity. Failure of filtration can be expressed by:

$$\text{Failure} = x > X_s \qquad [4.8]$$

Where x is the design variable, and X_s is the design performance standard.
Then the reliability (R) of filtration can be expressed as:

$$R = 1 - P(\text{Failure}) = 1 - P(x > X_s) \qquad [4.9]$$

Where, P is the probability. If the probability of failure ($x > X_s$) is characterized by the significance level ($\alpha, 0 \leq \alpha \leq 1$), then the reliability is given by $1-\alpha$. Reliability becomes confidence level when expressed as percentage. Therefore, Equation 4.9 can be written as:

$$1 - \alpha = P(x \leq X_s) \qquad [4.10]$$

In this study, negative power transformations were required to attain a normal distribution of filtration data. The following discussions will adhere to negative power transformations only. Figure 4.4 describes the distributional changes during negative power transformation. The failure zone, $P(x \leq X_s)$ is reversed in the x-axis during negative power transformation (Figure 4.4b). From the transformed unit normal distribution (Figure 4.4c), the probability of the acceptable region of filtration is expressed by:

$$P\left(-Z \geq \frac{X'_s - \mu'}{\sigma'}\right) = 1 - \alpha \qquad [4.11]$$

and

$$-Z_{1-\alpha} \geq \left(\frac{X'_s - \mu'}{\sigma'}\right) \qquad [4.12]$$

Where the accent indicates the transformed parameter. Therefore, the limiting conditions for filtration data to satisfy the reliability requirements would be:

$$\left(\frac{X'_s - \mu'}{\sigma'}\right) = -Z_{1-\alpha}, \quad \text{if } \lambda < 0 \qquad [4.13]$$

It should also be noted that for positive power transformation, Equation 4.13 would become:

$$\left(\frac{X'_s - \mu'}{\sigma'}\right) = Z_{1-\alpha}, \quad \text{if } \lambda > 0 \qquad [4.14]$$

4.7.2 Relationships Between Statistical Parameters

Niku et al. (1979) defined the Coefficient of Reliability (COR) as the ratio of the effluent standard to the design value. A similar concept was used in this study to describe the relationship between the standards or goals (X_s) to the design values (μ_d).

$$\mu_d = COR \bullet X_s \qquad (4.15)$$

In order to mathematically describe the COR, the relationships between the observed and transformed statistical parameters such as mean (μ), standard deviation (σ) and coefficient of variation (V, defined by σ/μ and often expressed in percentage) are required. Regression techniques were used with the assistance of SYSTAT®(1989) software to establish such relationships. Mathematical expressions of the relationship of the observed and transformed means are only available for some distributions. However, such a relationship for the data requiring a power transformation to achieve normality was not found in the literature. Therefore, functional relationships are obtained by regression (Figure 4.5 for the relationships between observed and transformed mean, Figure 4.6, for coefficient of variation). The best regression was obtained with the following relationships.

$$\mu' = \mu^{\lambda} \qquad [4.16]$$

$$V' = -\lambda \bullet V \qquad [4.17]$$

Where, λ is the power transformation required to normally distribute the data and V' is the coefficient of variation of the transformed data.

4.7.3 Model Verification

Equations 4.16 and 4.17 can be used to establish a mathematical expression between the observed μ and σ by substituting $V' = 100 \bullet \sigma' / \mu'$ and $V = 100 \bullet \sigma / \mu$ in Equation 4.17, and then substituting Equation 4.16.

$$\sigma = -\frac{\sigma'}{\lambda} \bullet \mu^{(1-\lambda)} \qquad [4.18]$$

The σ - μ relationship (Equation 4.18) is similar to the original assumption (Box et al. 1979) of power law (Equation 4.4). Therefore, the relationships of μ versus μ' and V versus V' are acceptable. However, the model constant σ' needed to be established. After transformation, standard deviation (σ') is homogeneous (constant) and estimated from the pooled variances. From the estimated σ', the k values (Equation 4.4) can also be back-calculated in conjunction with Equation 4.18 to satisfy $k = -\sigma'/\lambda$ (the back-calculated k is 0.6 for TURB, 0.2 for FRL and 0.2 for WPC). Except for TURB, back-calculated and tabulated k values (Table 4.2) differ substantially. Such differences in numerical constants are expected because of the scatter of data in σ - μ plots in FRL and WPC. In situations where the observed data is distributed close to normal, large scatter of σ are expected which may reduce the correlation coefficient of the model. Figures 4.2a, 4.2b and 4.2c depict: i) the observed σ - μ data; ii) model predictions with tabulated k values (Table 4.2, Equation 4.4); and, iii) model predictions with back-calculated k values (Equation 4.18) using the standard deviation of the transformed data. For TURB, the differences in model constants were not considerable. With the exception of one outlier in WPC (Figure 4.2c) and two in FRL (Figure 4.2b), the differences in k value can be neglected.

Therefore, the standard deviation of filtration data in the transformed scale was estimated from the pooled variances as 0.25 for TURB, 0.04 for FRL and 0.07 for WPC. These constant values will then be used to estimate the reliability of filtration using Equations 13 or 14.

4.8 Reliability-Based Filtration Design

The limiting reliability expression (Equation 4.13) can be rewritten by substituting for μ' from Equation 4.16. Therefore, the reliability based design equation (Equation 4.13) becomes:

$$\mu_d = \left(X_s^{\lambda} + \sigma' \bullet Z_{(1-\alpha)}\right)^{\left[\frac{1}{\lambda}\right]}, \quad \text{or,} \quad \mu_d^{\lambda} = X_s^{\lambda} + \sigma' \bullet Z_{(1-\alpha)}, \quad \text{for } (\lambda < 0) \qquad [4.19]$$

Where μ_d is the design value of the parameter of concern and $X'_s = (X_s)^{\lambda}$.

Then COR becomes:

$$\text{COR} = \left(1 + \frac{\sigma' \bullet Z_{(1-\alpha)}}{X_s^{\lambda}}\right)^{\left[\frac{1}{\lambda}\right]}, \quad \text{for } (\lambda < 0) \qquad [4.20]$$

It is evident from Equation 4.20 that COR of the filtration data is governed by (i) the standard deviation of the transformed data distribution (σ'); (ii) the coefficient of power transformation (λ) required to normally distribute the observed data; (iii) the required reliability ($1-\alpha$); and, (iv) the design standard (X_s). The variations of COR with the guidelines for TURB and FRL at different reliability values (confidence levels) are shown in Figure 4.7 and in Figure 4.8, respectively.

4.8.1 Sensitivity Analysis

The design equation (Equation 4.19) is influenced by the choice of the standards (X_S), the power transformation (λ), the pooled variance of the transformed data (σ) and the choice of the significance level (α). Among these, X_S and α are determined by the standards or guidelines, therefore, the sensitivity of the design regarding X_S and α is not important. However, λ and σ depend on the data distribution and the accuracy of the data analysis. Therefore, the sensitivity of the design equation to λ and σ' must be studied. The sensitivity analysis of the design equation can be classified into two components: i) the sensitivity due to the changes in λ; and ii) sensitivity due the error in σ'.

Component 1 (λ): The optimum λ for each design variable (TURB, FRL and WPC) in this study was obtained by trial and error. The universality of the above values was assessed by estimating λ values for different data subgroups (Tables 4.3 and 4.4) and then by choosing an appropriate λ to satisfy most of the data subgroups. To validate the universality, the sensitivity of the design equation must be verified within the optimum λ range of all data subgroups. Table 4.9 shows the percent error in μ_d for such range of λ and for different practical values of X_s and α. It should be noted that a change in λ would alter σ' (as given in parentheses in Table 4.9).

Component 2 (σ): Experimental errors may affect the estimated value of σ'. The sensitivity of the design equation to σ' was assessed at optimum λ (Table 4.10). However, the change in σ' caused by experimental error is expected to be less than that caused by the change in λ.

At low turbidity standards (0.1 NTU) the sensitivity of the design equation was very little within a large range of λ (Table 4.9). An error of 14 percent is expected with 20 percent change in σ' (Table 4.10). This suggests that the design procedure can be applied more effectively at low turbidity levels (0.1 NTU). For slight changes in λ (± 0.5), the design equation was less sensitive (< 13%, Table 4.8). The sensitivity of FRL design to λ and σ' was lower than that of effluent turbidity data. WPC design had the least sensitivity to changes (Tables 4.9 and 4.10). The sensitivity generally increased with higher standards (X_s).

Based on the sensitivity analysis, the design procedure (described by Equation 4.19) can be adopted: i) if the operating condition of a treatment plant is similar to that of Rossdale water treatment plant (i.e., satisfying the boundary conditions of this study); or ii) if the value of the standards (X_S) is lower (i.e., ≤ 0.1 NTU for TURB, ≤ 24 h for FRL). If the above conditions were not met, applying the concepts of data transformation and reliability-based design procedure (as described in this thesis) to the results of short-term pilot studies would be necessary. Because of the sensitivity of the design equation to changes in σ' due to experimental error, conducting a short-term pilot study to estimate σ' would further improve the acceptability of this design procedure.

4.8.2 Design Summary

The guidelines for Canadian drinking water quality suggest that the average effluent turbidity of combined filters not to exceed the standard (e.g., 1 NTU = X_s) for a specified percentage of time (e.g., 95%). The percentage compliance time can be considered as the reliability and the significance level (α) is chosen accordingly ($\alpha = 0.05$ for the example). If the boundary conditions of this study (raw water quality, pretreatment processes such as coagulation, lime-softening and clarification, filter influent quality and plant operations) are met, the design effluent turbidity could be determined either by:

(i) using Equation 4.19 with appropriate values from Tables 4.7 and 4.8; or

(ii) using Equation 4.15 with COR obtained from Figure 4.7; or

(iii) using Figure 4.9 which graphically illustrate the design effluent turbidity.

If the boundary conditions of this study are not met, then λ and σ' could be established from short-term pilot studies conducted at the plant operating conditions, using the data transformation procedure outlined in this study. Such results, together with Equation 4.19 could be used to establish design values.

The design effluent turbidity (μ_d) from the above approach is 0.42 NTU. Therefore, to satisfy the turbidity standards (1 NTU for 95% of the operating time) during long-term operations, the average effluent turbidity of the filter obtained from a short duration pilot testing or pre-established values should be less than 0.42 NTU. Similar procedure can be adopted for FRL and WPC values.

The data in the above example is based on the Guidelines for Canadian Drinking Water Quality (1993). In view of the above, the average turbidities of different filter media obtained from this study (Table 4.1) were compared. All average turbidities were less than 0.42 NTU, thus no violation of the current federal guidelines would occur. In order to comply with the licensing requirements of the Province of Alberta (X_s = 1 NTU and the reliability is 99%), the design average turbidity (μ_d) will be 0.32 NTU. Table 4.1 suggests that the effluent turbidity of the anthracite/sand dual-media filters lies closer to the limit when operated at 12.5 m/h. This has to be taken into consideration in the selection of media. If the USEPA (1989) guidelines (0.5 NTU, 95% of operating time) are to be adopted, then μ_d will be 0.25 NTU (Figure 4.9). In such situations, only the use of crushed quartz is justified (Table 4.1) to meet the USEPA guidelines at all operating conditions in this study.

The mean value of the parameter of concern (μ_d) that was obtained from a pilot plant operated for a short period, may be used in conjunction with Equation 4.19 to predict the long term-average (X_s) at a specified reliability.

Some regulatory agencies set a percentage of compliance to the effluent turbidity standards (i.e., the effluent turbidity shall be less than 1 NTU for 95% of the filter operating time). In addition to the health related factors, the filtration process should be able to satisfy the selected percentage compliance. Some treatment plants may have in-plant guidelines which are lower than that imposed by the regulatory agencies. Figure 4.9 or Equation 4.19 can be used to choose practical values for the stringent in-plant effluent turbidity standards and percentage compliance with the standards (i.e., reliability) in terms of achievability in treatment plants.

4.9 Conclusions

Reliability of filtration is characterized by a probabilistic model that leads to the estimation of reliability based on confidence level. Such a reliability model can be used in rational design of filtration. Design equations and diagrams have been recommended for the estimation of the design value based on the coefficient of reliability. Using this rational approach will facilitate proper design of filtration that can comply with the regulatory standards on a long-term basis from the results obtained in a brief pilot study or the data obtained from available literature.

Filtration data distributions of the effluent turbidity, filter run length and water production capacity are not normally distributed. Therefore, conclusions drawn from simple averages of the above parameters are not appropriate. Due to the non-normality of the observed data, the long-term predictions from the experiments conducted during short period may not be reliable.

Appropriate power transformations are required to normally distribute the observed data. Negative power transformations to the power (λ) of -0.4, -0.2, and -0.3 of the observed effluent turbidity, filter run length and water production capacity, respectively, are required to transform the distribution to normal from which statistically correct inferences about filtration could be made. The standard deviations (σ) of the filtration data on the transformed normal scale are homogeneous and 0.25, 0.04 and 0.07 for effluent turbidity, filter run length and water production capacity, respectively. These results could be applied to situations where the boundary conditions of this study (raw water quality, pretreatment, filter influent quality and operational procedure) prevailed. If not, the concept of data transformation and reliability-based design, as outlined in this study, could be used in conjunction with short-term pilot studies.

4.10 References

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4.11 Notation

The following symbols are used in this paper:

$1-\alpha$ = probability of compliance, confidence level (when expressed in percentage);

α = probability of failure, significance level;

COR = coefficient of reliability;

FRL = filter run length;

k = model constant;

λ = power transformation required to normalize the observed data ($x' = x^{\lambda}$);

R = reliability (=$1-\alpha$, expressed in percentage);

σ = apparent standard deviation (observed data);

σ' = standard deviation of normalized (transformed) data;

TURB = effluent turbidity;

V = coefficient of variation = $100 \cdot \sigma / \mu$;

V' = coefficient of variation (transformed data) = $100 \cdot \sigma' / \mu'$;

WPC = water production capacity;

x = observed data;

x' = transformed data (normalized, constant variance);

X_s = design standard (i.e., TURB, FRL and WPC);

$Z_{(1-\alpha)}$ = Standard normal variate;

μ = mean;

μ' = mean (transformed data).

Subscripts

d = design parameter;

s = standards;

$1-\alpha$ = confidence level or reliability (in percentage).

Superscripts

' = transformed parameter.

Table 4.1 Observed Filtration Data

Flow rate (m/h)	Poly. dose (mg/L)	Turbidity				Filter Run Length				Water Production Capacity[1]			
		μ (NTU)	s (NTU)	n -	Skew -	μ (h)	s (h)	n -	Skew -	μ (m^3)	s (m^3)	n -	Skew -
(a) Anthracite/Sand Dual-media													
3.50	0.00	0.11	0.05	16	1.1	97.7	11.7	6	-0.5	6.0	0.7	6	-0.5
3.50	0.02	0.09	0.00	5	0.9	89.0	-	1	-	5.5	-	1	-
3.50	0.10	0.09	0.01	4	1.4	65.0	-	1	-	4.0	-	1	-
8.00	0.00	0.08	0.02	12	-0.2	98.8	6.7	6	0.4	14.0	0.9	6	0.4
8.00	0.06	0.10	0.01	13	-0.3	19.1	8.8	11	0.8	2.7	1.2	11	0.8
12.5	0.00	0.24	0.07	14	-0.8	13.8	3.7	19	0.8	3.1	0.8	19	0.8
12.5	0.02	0.39	0.13	3	1.6	12.0	2.1	4	-0.1	2.7	0.5	4	-0.10
12.5	0.10	0.12	0.00	4	0.6	12.7	0.8	3	0.9	2.8	0.2	3	0.9
(b) Crushed Quartz Mono-media													
3.50	0.00	0.05	0.01	24	0.1	37.3	9.5	14	-0.1	2.3	0.6	14	-0.1
3.50	0.02	0.05	0.01	4	0.8	30.3	9.5	3	0.2	1.9	0.6	3	0.2
3.50	0.10	0.07	0.01	4	1.2	22.3	2.5	3	0.6	1.4	0.2	3	0.6
8.00	0.00	0.05	0.00	7	1.1	45.1	7.2	6	0.0	6.4	1.0	6	0.0
8.00	0.06	0.07	0.01	18	0.3	14.6	3.5	17	0.6	2.1	0.5	17	0.6
12.5	0.00	0.09	0.04	13	1.1	8.1	3.2	20	-0.1	1.8	0.7	20	-0.1
12.5	0.02	0.07	0.00	3	-1.0	7.4	1.0	4	-1.1	1.6	0.2	4	-1.1
12.5	0.10	0.11	0.03	6	-0.4	6.6	2.2	5	-0.4	1.5	0.5	5	-0.4
(c) Existing Filter Sand Mono-media													
3.50	0.00	0.08	0.02	17	0.9	44.3	9.6	9	0.6	2.7	0.6	9	0.6
8.00	0.00	0.14	0.04	9	0.7	16.6	4.0	7	-0.2	2.3	0.6	7	-0.2
12.5	0.00	0.25	0.10	6	0.7	6.8	2.4	5	0.2	1.5	0.5	5	0.2

[1] per filter cycle

n = number of filter runs at specified conditions

Table 4.2 Determination of λ for Box-Cox Transformation

Parameter	k	λ	R	χ^2
TURB	0.531±0.103	-0.39±0.14	0.938	0.003
FRL	1.091±0.500	0.50±0.12	0.756	85.2
WPC	0.421±0.082	0.65±0.13	0.546	0.947

Table 4.3a Acceptance Range of λ for Transformation to Normality-All Media Types

Case*	Test** index	λ_{TURB}			λ_{FRL}			λ_{WPC}		
		Low	Opt	Upper	Low	Opt	Upper	Low	Opt	Upper
1	W	-1.2	-0.8	-0.4	-	-0.25 [2]	-	-1	-0.9	-0.8
	α_1	-0.88	-0.63	-0.39	-0.35	-0.19	-0.02	-0.52	-0.37	-0.23
	β_2	-1.8	-0.14	0.1	-0.6	0.31	0.6	-0.6	-0.33	-0.1
2	W	-0.7	-0.45	-0.2	-	0.05 [2]	-	-1	-0.7	-0.25
	α_1	-0.9	-0.53	-0.2	-0.2	-0.04	0.2	-0.45	-0.27	-0.1
	β_2	-2.3	-1.76	-1.2	-0.7	-0.46	-0.2	-0.6	-0.2	0.2
	β_2 [1]	0.1	0.44	0.8	0.4	0.71	1.1	-	-	-
3	W	-0.5	-0.1	0.4	0.3	-	>.3	1.1	-	>1.1
	α_1	-1.4	-1.05	-0.8	-0.45	-0.24	-0.1	-0.6	-0.27	0.1
	β_2	-2.1	-1.25	-0.7	-0.4	-0.2	-0.04	-0.7	0.0001	0.7

* Case 1: runs with both polymer and no polymer Case 2: runs with no polymer
Case 3: runs with polymer

** Test Index: W: W-test $\alpha 1$: Pearson's test $\beta 2$: Pearson's test

[1]: second acceptance region [2]: best possible transformation (no acceptance region)

Table 4.3b Acceptance Range of λ for Transformation to Normality-Individual Media

Case*	Test** index	λ_{TURB}			λ_{FRL}			λ_{WPC}		
		Low	Opt	Upper	Low	Opt	Upper	Low	Opt	Upper
					Anthracite Sand Dual-media					
1	W	-2.5	-2	-1.5	-	-5.4^{2}	-	-1.9	-1.3	-0.8
	α_1	-1.2	-0.85	-0.5	-2.3	-1.45	-0.5	-1.2	-0.73	-0.3
	β_2	-1.4	-0.98	0.4	-3.8	-2.98	-2.3	-2	-0.06	0.5
	$\beta_2{}^1$	-	-	-	0.9	2.58	4.7	-	-	-
2	W	-4	-2.4	-0.7	-	1.9^{2}	-	-1.1	-0.2	0.7
	α_1	-1.2	-0.49	0.6	-2.2	-1	2.7	-2	-0.95	0.03
	β_2	-2	-1.42	-0.9	-3.7	-2.71	-2	-3.7	-2.58	-1.7
	$\beta_2{}^1$	1.1	1.83	2.7	-	-	-	-0.08	1	3.6
3	W	-9.8	-5.2	-3.2	-	-4.5	-	-2.8	-1.8	-0.7
	α_1	-4.8	-3.1	-2.1	-3.8	-2.08	-0.6	-1.7	-0.35	0.5
	β_2	-8.7	-2.4	-1.4	-4.7	-3.55	-2.5	-5.2	0.49	1.3
	$\beta_2{}^1$	-	-	-	-1	-0.3	0.2	-	-	-
					Crushed Quartz Mono-media					
1	W	-1.1	-0.2	0.5		0.5^{2}		-3	-2.2	-1.4
	α_1	-1.2	-0.65	-0.2	-0.3	0.03	0.4	-0.5	-0.28	-0.05
	β_2	-0.4	0.08	0.5	-0.8	-0.50	-0.2	-0.6	-0.3	0.1
	$\beta_2{}^1$	-	-	-	0.8	1.39	2.2	-	-	-
2	W	-	-3.4^{2}	-	2.3	5.4	10.7	-2.2	-1.4	-0.6
	α_1	-2.3	-1.3	-0.5	-0.36	0.4	1.5	-0.4	-0.13	0.2
	β_2	-0.6	-0.15	0.4	-1.1	-0.69	-0.33	-0.9	0.1	0.9
3	W	-	-0.7^{2}	-	-	0.4^{2}	-	-2.4	-1.5	-0.6
	W^1	-	-	-	-	-	-	0.4	1.3	2.6
	α_1	-2	-1.1	-0.3	-0.3	0.15	0.6	-0.2	0.41	1.1
	β_2	-2.5	-1	0.5	-0.6	-0.11	0.9	-0.3	0.5	1.6
					Exsisting Filter Sand Mono-media					
2	W	-1	0.2	1.3	-0.8	-0.1	0.6	1.1	3.85	6.9
	α_1	-2	-1	-0.2	-0.4	0.4	1.5	0.1	1	2.1
	β_2	-2.9	-2.18	-1.3	-1	-0.51	-0.1	-0.6	0.3	2.9
	$\beta_2{}^1$	-0.6	0.04	0.5	1.2	1.86	2.7	-	-	-

* Case 1: runs with both polymer and no polymer   Case 2: runs with no polymer
Case 3: runs with polymer

** Test Index: W: W-test $\alpha 1$: Pearson's test $\beta 2$: Pearson's test

^{1}: second acceptance region ^{2}: best possible transformation (no acceptance region)

Table 4.4 Acceptance Range of λ for Transformation to Stabilize Variances

Case*	Test** index	λ_{TURB}			λ_{FRL}			λ_{WPC}		
		Low	Opt	Upper	Low	Opt	Upper	Low	Opt	Upper
All Media Types										
1	Z	0.5	0.7	0.9	-	0.3	-	0.1	0.4	0.7
	$\chi 2$	0.2	0.8	1.3	0.2	0.4	0.7	0	0.6	0.9
2	Z	<-20	-20	1	<.8	-0.6	0.8	-0.17	0.3	0.8
	$\chi 2$	0.2	1.1	1.5	0.3	0.6	0.8	0.1	0.44	0.8
3	Z	<1.6	0.9	1.6	-1.1	0.5	>-1.1	-0.1	0.5	1
	$\chi 2$	-2.1	8	>-2.1	all	0.7	all	-0.1	0.4	0.9
Anthracite Sand Dual-media										
1	Z	-0.1	0.7	1.2	0.6	0.3	0.1	-0.5	0.3	1.2
	$\chi 2$	-0.2	0.8	1.4	0.1	0.4	0.7	-0.5	-0.1	0.2
2	Z	-3.1	0.9	>-3.1	-1.9	0.2	1.6	-7.2	-2.9	0.4
	$\chi 2$	-2.87	0.8	>-2.87	-0.5	0.3	>-.5	-0.8	0.2	0.9
3	Z	0.1	0.7	1.2	-	-0.6	-	-0.7	-0.7	-0.7
	$\chi 2$	0	1	1.5	-0.7	-0.6	-0.5	-0.4	-0.4	-0.4
Crushed Quartz Mono-media										
1	Z	-0.3	0.65	1.3	-2.5	-0.6	-0.01	-1.6	-1.2	-0.6
	$\chi 2$	0.1	0.8	1.2	-	0.01	-	-1	-0.7	-0.4
2	Z	-0.2	0.9	1.7	-1.2	-0.1	1.6	-1	0	0.6
	$\chi 2$	-0.3	0.7	1.5	<.01	-0.6	0.01	-2.4	-1.5	-0.8
3	Z	-1.4	0.8	4.4	-1.8	-1.1	-0.5	-1.2	-0.6	-0.1
	$\chi 2$	-1.5	-0.3	1.2	-3.2	-1.3	-0.4	-1.1	-0.4	0
Exsisting Filter Sand Mono-media										
2	Z	-5.7	0.2	5.7	-6.8	-0.2	1.3	-4.2	-1.8	0.5
	$\chi 2$	-1.9	0.5	3.7	<.5	-0.7	0.5	-1.2	-0.8	-0.5

* Case 1: runs with both polymer and no polymer Case 2: runs with no polymer
Case 3: runs with polymer

** Test Index: $\chi 2$: Bartlett's test Z: Levene's test

[1]: second acceptance region [2]: best possible transformation (no acceptance region)

Table 4.5 Transformed Filtration Data*

Flow rate (m/h)	Poly. dose (mg/L)	TURB			FRL			WPC		
		μ (NTU)	σ (NTU)	Skew -	μ (h)	σ (h)	Skew -	μ (m^3)	σ (m^3)	Skew -
					Anthracite/Sand Dual-media					
3.5	0	2.49	0.38	-0.9	0.40	0.01	0.60	0.58	0.02	0.61
3.5	0.02	2.59	0.05	-0.8	0.41			0.60		
3.5	0.1	2.62	0.09	-1.3	0.43			0.66		
8	0	2.78	0.33	0.5	0.40	0.01	-0.31	0.45	0.01	-0.31
8	0.06	2.50	0.12	0.7	0.57	0.05	-0.32	0.77	0.10	-0.28
12.5	0	1.83	0.28	1.6	0.60	0.03	-0.34	0.72	0.05	-0.30
12.5	0.02	1.49	0.19	-1.4	0.61	0.02	0.47	0.75	0.04	0.51
12.5	0.1	2.36	0.02	-0.5	0.60	0.01	-0.86	0.73	0.01	-0.85
					Crushed Quartz Mono-media					
3.5	0	3.29	0.23	0.3	0.49	0.03	0.44	0.79	0.06	0.47
3.5	0.02	3.26	0.14	-0.5	0.51	0.03	0.41	0.84	0.08	0.46
3.5	0.1	2.93	0.12	-1.0	0.54	0.01	-0.40	0.91	0.03	-0.38
8	0	3.44	0.05	-1.0	0.47	0.02	0.39	0.58	0.03	0.42
8	0.06	2.89	0.17	-0.1	0.59	0.03	0.20	0.81	0.06	0.26
12.5	0	2.66	0.36	-0.2	0.67	0.06	0.75	0.87	0.12	0.80
12.5	0.02	2.88	0.08	1.1	0.67	0.02	1.29	0.87	0.04	1.30
12.5	0.1	2.49	0.29	1.1	0.69	0.05	1.06	0.91	0.11	1.12
					Existing Filter Sand Mono-media					
3.5	0	2.79	0.21	-0.2	0.47	0.02	-0.15	0.75	0.05	-0.12
8	0	2.21	0.21	-0.3	0.57	0.03	0.66	0.78	0.06	0.69
12.5	0	1.81	0.29	0.0	0.69	0.05	0.36	0.90	0.10	0.40

* according to equations 4.5, 4.6, and 4.7

Table 4.6 Comparison of Some t-test Inferences of the Observed and Transformed Data

Parameter	Flow Rate (m/h)	Poly. Dose (mg/L)	Media Type -	Statistical Inference at 95% Confidence Level	
				Observed Data	Transformed Data
				Comparison of Media Types	
TURB	8.0	0	-	D>B>C	D>B, D>C
TURB	12.5	0	-	B>D>C	B>C, D>C
TURB	12.5	0.1	-	B>C	inconclusive
WPC	3.5	0	-	B>D>C	B>D, B>C
WPC	8.0	0.06	-	B<C	inconclusive
WPC	12.5	0	-	B>C, B>D	B>D
FRL	12.5	0.1	-	B>C	inconclusive
FRL	3.5	0	-	B>D>C	B>D, B>C
FRL	12.5	0.1	-	B>C	inconclusive
				Comparison of Filtration Rates	
TURB	-	0.00	C	12.5>3.5>8	12.5>3.5, 12.5>8
FRL	-	0.00	C	8>3.5>12.5	8>12.5, 3.5>12.5
				Comparison of Polymer Dosage	
TURB	3.5	-	B	0>.02>.1	inconclusive
TURB	3.5	-	C	.1>0, .02>0	.1>0, .1>.02
FRL	3.5	-	B	0>.1, .02>.1	0>.1
TURB	8.0	-	B	.06>0	inconclusive
TURB	12.5	-	B	.02>0>.1	02>.1
TURB	12.5	-	C	.02>0>.1	inconclusive

Table 4.7 Summary of Design Parameters

Parameter	TURB	FRL	WPC
λ	-0.4	-0.2	-0.3
σ'	0.25	0.04	0.07

Table 4.8 Values of Standardized Normal Distribution (Box et al 1978)

Reliability (%)	α	$Z_{(1-a)}$
99.99	0.0001	3.755
99.9	0.001	3.09
99	0.01	2.326
95	0.05	1.645
90	0.1	1.405
80	0.2	1.282
70	0.3	0.8
60	0.4	0.525
50	0.5	0.253

Table 4.9 Sensitivity of Equation 4.19 to changes in λ.

a. Effluent Turbidity (Optimum λ = -0.4)

	λ =	0.1 (0.02)	-0.1 (0.03)	-0.2 (0.08)	-0.35 (0.19)	-0.4 (0.25)	-0.45 (0.31)	-0.6 (0.59)	-0.8 (1.28)	-1 (2.64)	-2 (77.2)
X_s	α	Percent Error in μ_d									
0.1	0.01	10	5	3	1	0	-1	-2	-3	-3	0
0.1	0.05	6	3	2	0	0	0	-1	-1	-1	4
1	0.01	-90	-53	-35	-8	0	8	27	45	57	77
1	0.05	-66	-41	-28	-7	0	7	25	43	56	79
2	0.01	-158	-92	-58	-13	0	11	38	58	70	85
2	0.05	-111	-70	-46	-11	0	10	36	58	70	87

b. Filter Run Length (Optimum λ = -0.2)

	λ =	0.90 (3.9)	-0.10 (0.022)	-0.15 (0.031)	-0.2 (0.04)	-0.25 (0.041)	-0.30 (0.044)	-0.40 (0.047)	-0.60 (0.046)	-0.80 (0.042)	-2 (0.013)
X_s	α	Percent Error in μ_d									
24	0.01	7	-3	-2	0	2	4	7	15	23	51
24	0.05	-3	-3	-1	0	2	3	7	14	22	53
72	0.01	-96	-13	-6	0	6	12	23	42	55	80
72	0.05	-65	-10	-5	0	5	10	20	39	53	82
120	0.01	-136	-18	-9	0	9	17	32	54	67	87
120	0.05	-88	-14	-7	0	7	14	28	50	65	88

c. Water Production Capacity (Optimum λ = -0.3)

	λ =	0.5 (0.22)	0.1 (0.03)	-0.2 (0.05)	-0.25 (0.06)	-0.3 (0.07)	-0.35 (0.08)	-0.4 (0.09)	-0.6 (0.13)	-1 (0.18)
X_s	α	Percent Error in μ_d								
1	0.01	58	21	4	2	0	-2	-4	-10	-20
1	0.05	39	14	3	1	0	-1	-3	-7	-13
10	0.01	-89	-46	-11	-5	0	5	10	27	48
10	0.05	-62	-35	-9	-4	0	4	9	25	48
20	0.01	-155	-84	-19	-9	0	9	16	41	65
20	0.05	-102	-61	-16	-8	0	7	15	38	65

values in parentheses indicate σ' of the transformed data for corresponding λ.

Table 4.10 Sensitivity of Equation 4.19 to changes in σ'.

a. Effluent Turbidity (estimated σ' = 0.25)

	σ' =	0.020	0.031	0.077	0.190	0.25	0.309
X_S	α	Percent Error in μ_d					
0.1	0.01	45	43	37	14	0	-22
0.1	0.05	33	32	26	10	0	-14
1	0.01	86	85	80	47	0	-191
1	0.05	70	68	61	29	0	-63
2	0.01	96	96	94	72	0	-4877
2	0.05	83	82	76	43	0	-142

b. Filter Run Length (estimated σ' = 0.04)

	σ' =	0.013	0.023	0.031	0.036	0.041	0.04	0.044	0.047
X_S	α	Percent Error in μ_d							
24	0.01	-60	-30	-12	-2	8	0	13	17
24	0.05	-41	-21	-8	-1	6	0	9	13
72	0.01	-77	-37	-14	-2	9	0	15	20
72	0.05	-52	-26	-10	-1	7	0	11	16
120	0.01	-87	-41	-16	-2	10	0	16	22
120	0.05	-58	-29	-11	-2	7	0	12	17

c. Water Production Capacity (estimated σ' = 0.07)

	σ' =	0.028	0.052	0.064	0.07	0.084	0.093	0.154	0.179
X_S	α	Percent Error in μ_d							
1	0.01	-14	-7	-3	0	2	4	2	1
1	0.05	-10	-5	-2	0	2	3	2	0
10	0.01	-27	-14	-6	0	4	8	4	1
10	0.05	-19	-10	-4	0	3	6	3	1
20	0.01	-33	-17	-7	0	4	9	5	1
20	0.05	-23	-12	-5	0	3	7	4	1

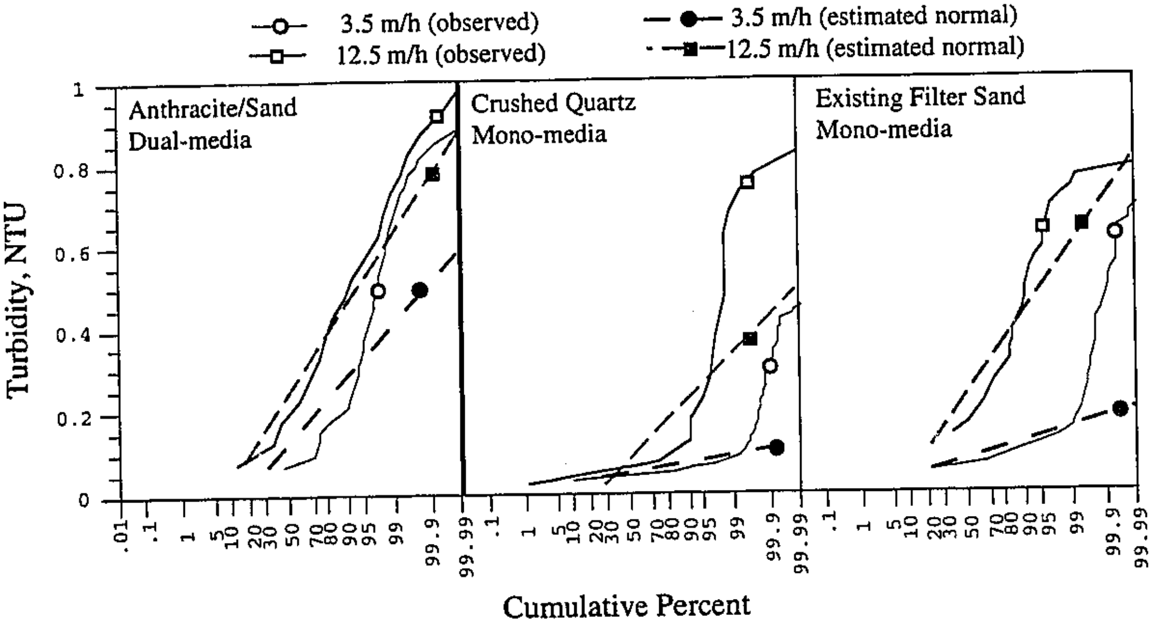

Figure 4.1 Normal Probability Plots of the Observed Data and Estimated Normal Curve

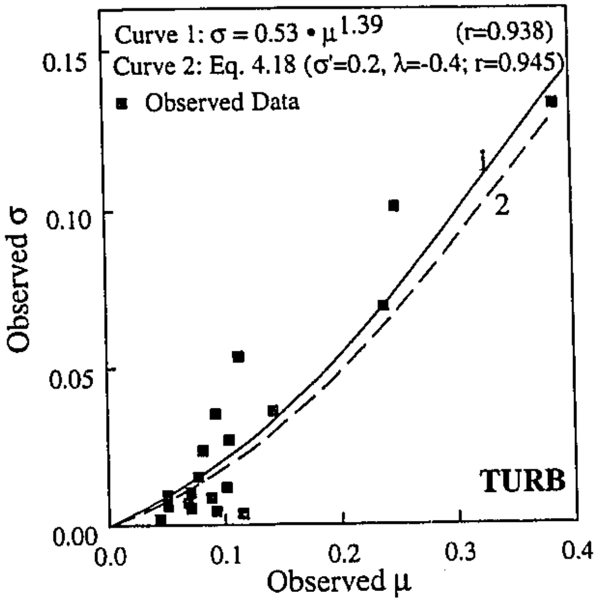

Figure 4.2a Correlations Between the Observed Mean and Standard Deviations - Effluent Turbidity

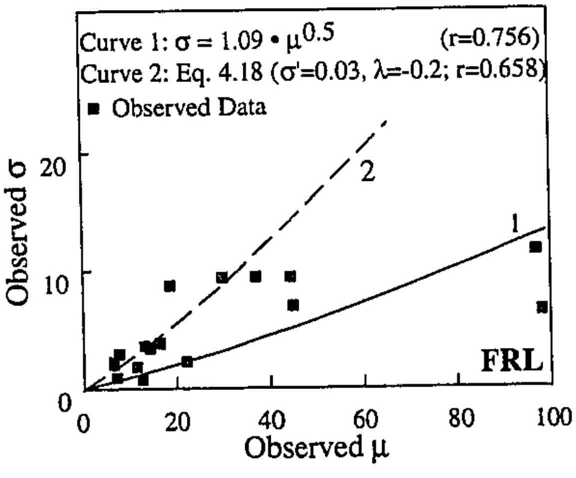

Figure 4.2b Correlations Between the Observed Mean and Standard Deviations-Filter Run Length

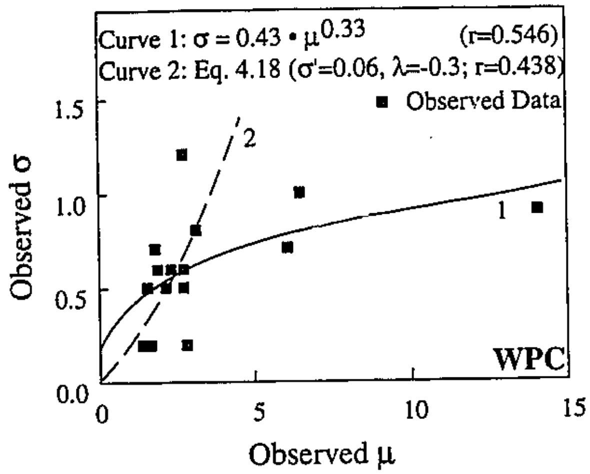

Figure 4.2c Correlations Between the Observed Mean and Standard Deviations-Water Production Capacity

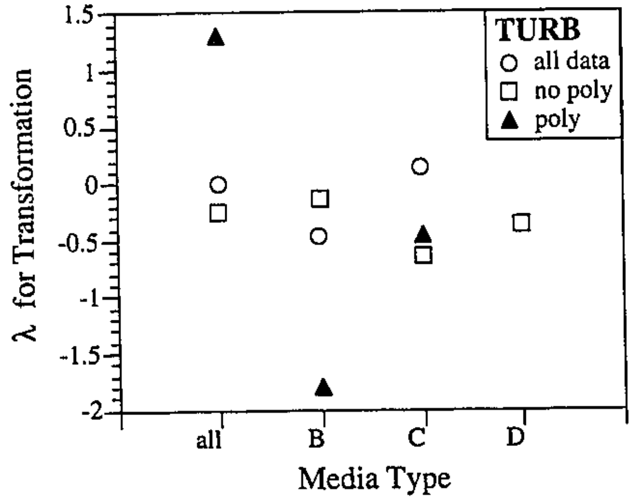

Figure 4.3a Transformation (λ) for Various Groups of Data - Effluent Turbidity

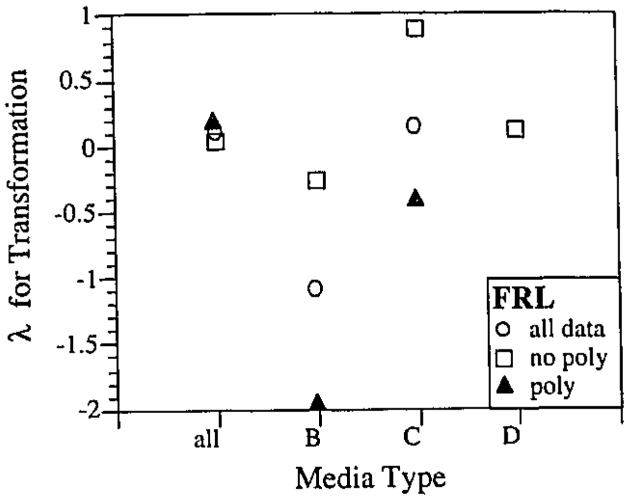

Figure 4.3b Transformation (λ) for Various Groups of Data - Filter Run Length

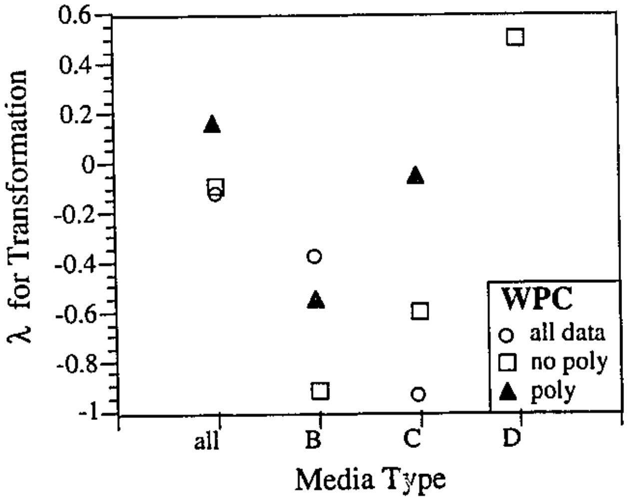

Figure 4.3c Transformation (λ) for Various Groups of Data - Water Production Capacity

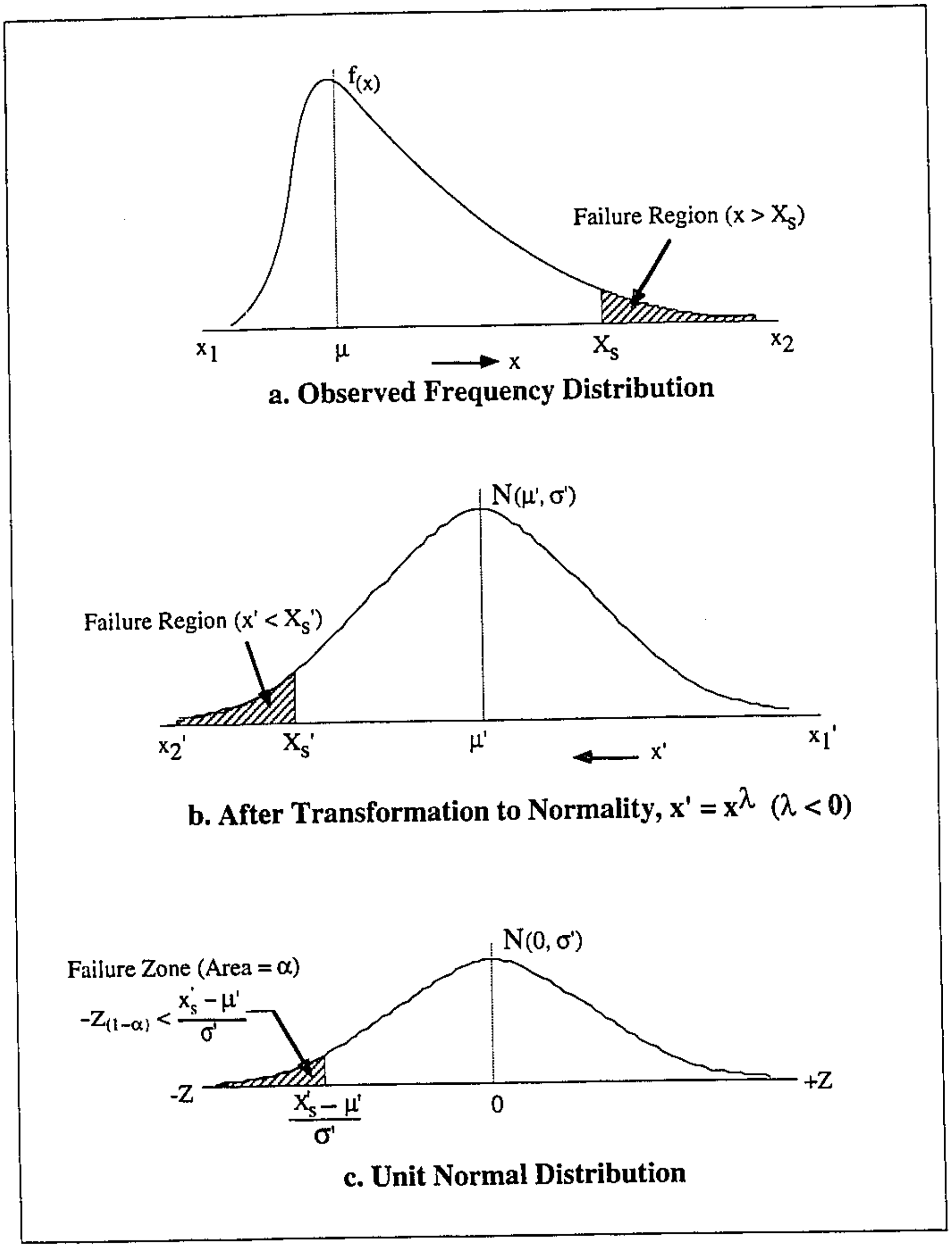

Figure 4.4 Distributions and Failure Regions During Negative Power Transformation

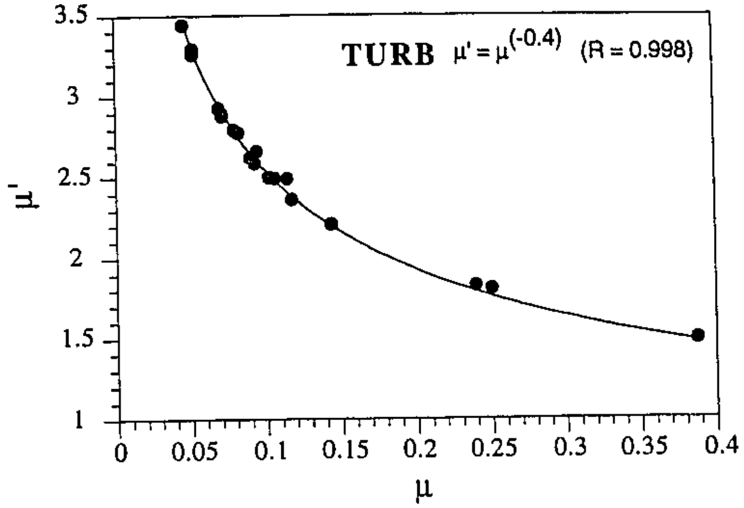

Figure 4.5a Relationships Between the Observed and Transformed Means for Effluent Turbidity

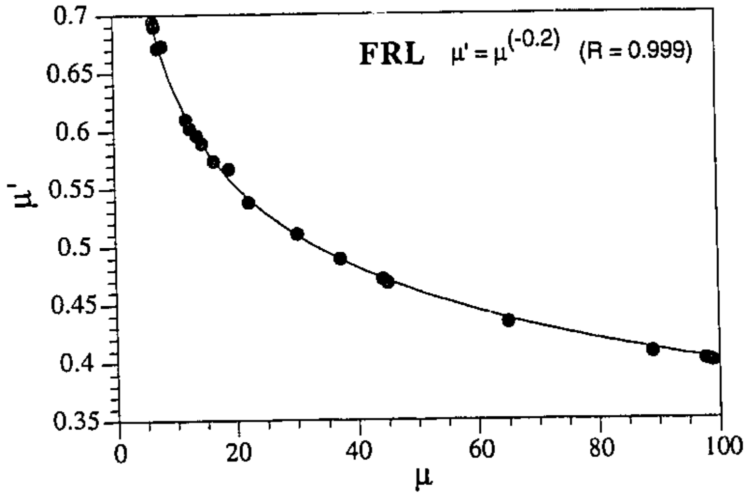

Figure 4.5b Relationships Between the Observed and Transformed Means for Filter Run Length

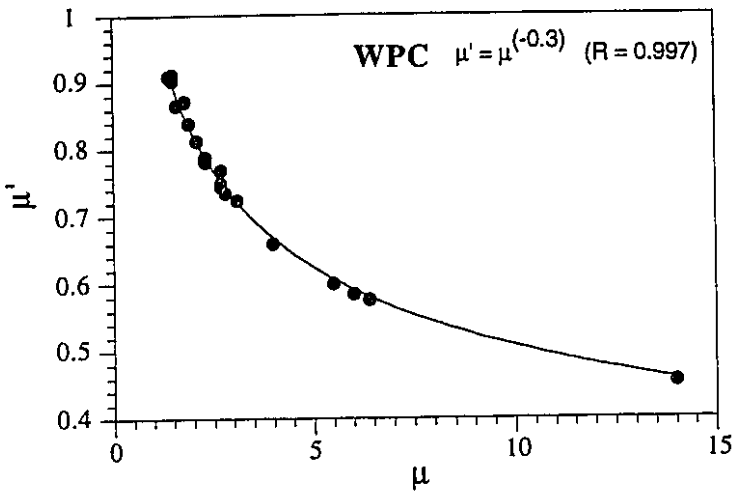

Figure 4.5c Relationships Between the Observed and Transformed Means for Water Production Capacity

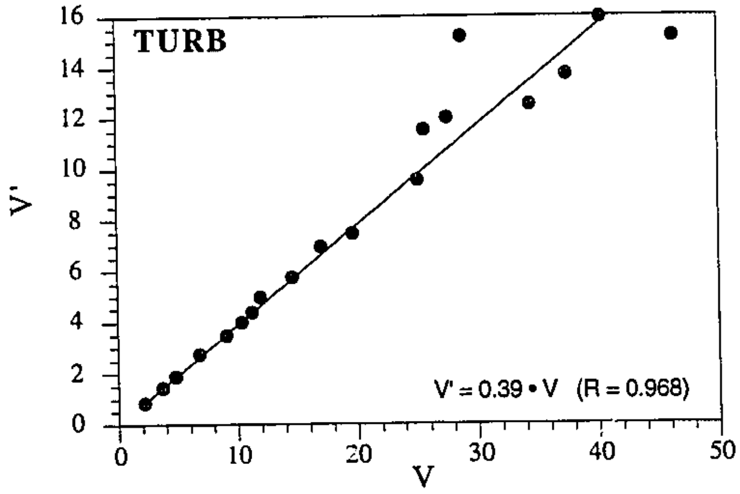

Figure 4.6a Relationships Between Observed and Transformed Coefficients of Variation for Effluent Turbidity

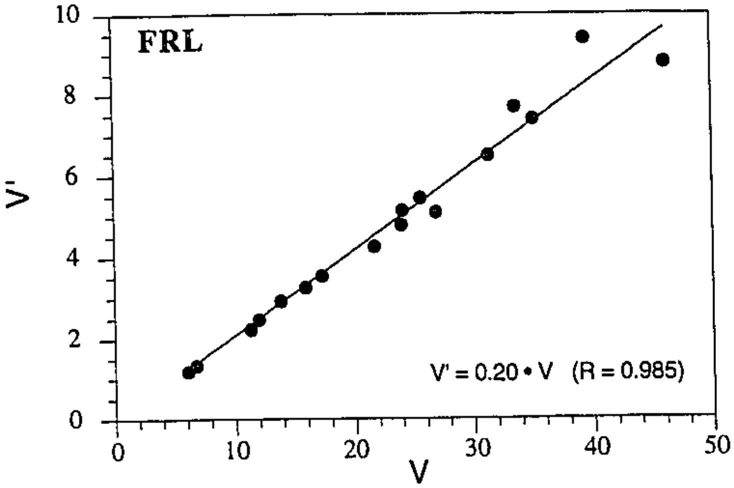

Figure 4.6b Relationships Between Observed and Transformed Coefficients of Variation for Filter Run Length

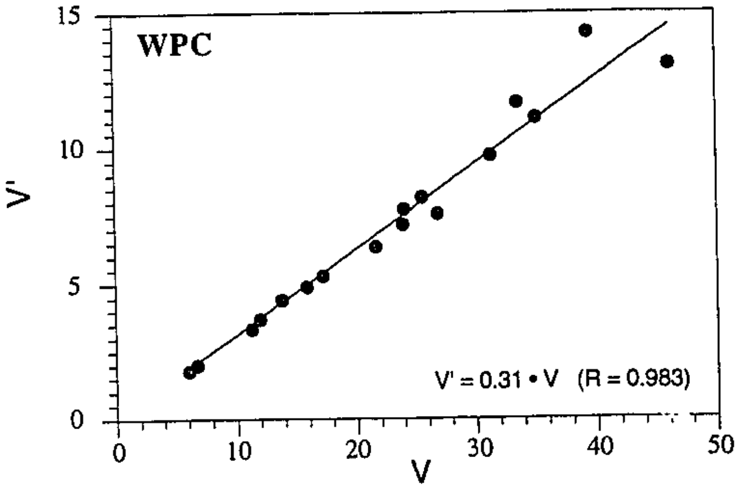

Figure 4.6c Relationships Between Observed and Transformed Coefficients of Variation for Water Production Capacity

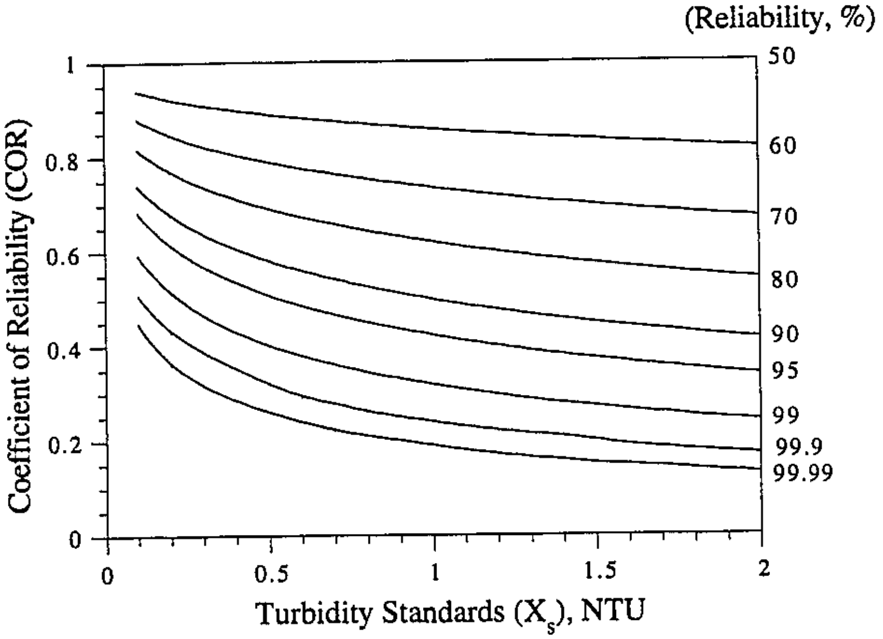

Figure 4.7 Diagram for the Determination of COR - Effluent Turbidity (for $\lambda = -0.4$, $\sigma' = 0.25$ along with the boundary conditions of this study)

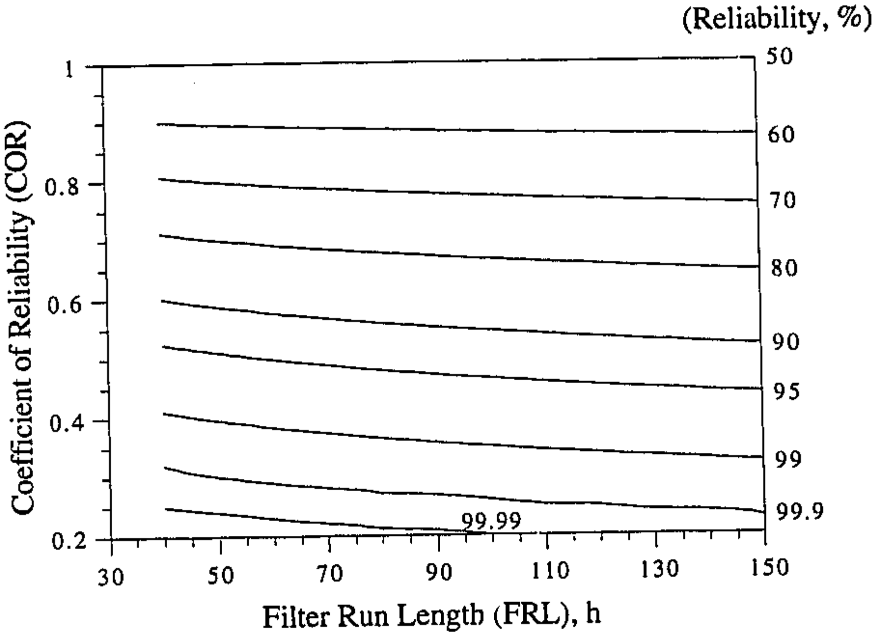

Figure 4.8 Diagram for the Determination of COR - Filter Run Length (for $\lambda = -0.2$, $\sigma' = 0.04$ along with the boundary conditions of this study)

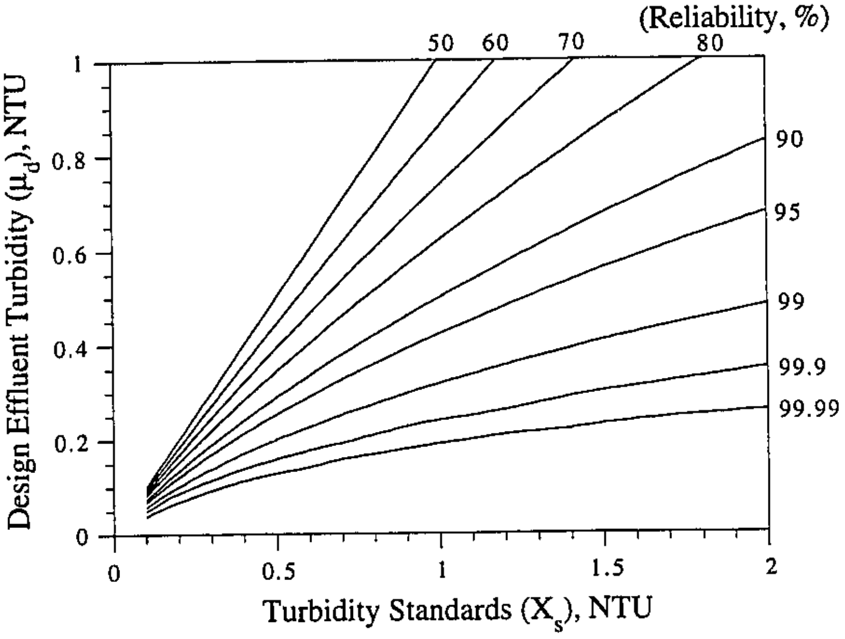

Figure 4.9. Reliability-based Design for Effluent Turbidity
(for $\lambda = -0.4$, $\sigma' = 0.25$ along with the boundary conditions of this study)

Chapter 5

Optimization of Filter Ripening Sequence

5.1 Introduction

Previous research has indicated that the period of initial effluent degradation after backwashing filters, is influenced by: i) the remnant water remaining within the filter media at the end of backwash (Amirtharajah and Wetstein, 1980); ii) the influent quality (Francois and Van Haute, 1985); and iii) the hydraulic conditions of the filter. An increased transport of potentially pathogenic microorganisms through the filter unit may be associated with the initial period of effluent degradation (Bucklin, et al. 1988). Concern about the initial portion of the filter run is due to the association of high turbidities with high particle counts (McCoy and Olson, 1986), and with high number of microorganisms (Logsdon et al. 1985). However, regardless of the number of organisms associated with turbidity, high effluent turbidities are undesirable due to the implications for disinfection and the more stringent turbidity guidelines. Turbidity is also believed to act as a carrier for nutrients that result in biological activity and water quality deterioration in the distribution system. It may exert a significant increase in the disinfectant demand, thereby reducing the disinfectant residual in the distribution lines. As a result, high turbidity effluent occurring during the filter ripening should not enter the finished water.

Logsdon et al. (1985) conducted pilot plant studies and concluded that Giardia cyst concentrations may be higher than usual during the first portion of a filter run and the operators should consider a filter-to-waste procedure at the beginning of a new run. The use of a filter-to-waste procedure at the beginning of the filter run can be effective in restricting the initial period of poor quality effluent from entering the finished water.

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Excessive consumption of raw water due to the significant length of filter ripening will increase the treatment plant costs. However, complete elimination of the filter-to-waste procedure is not desirable as the initial effluent may contain Giardia cysts, which may be associated with turbidity causing particles during the filter ripening. Even a low dose of Giardia cysts can be infective (Kirner et al. 1978). In addition, the high initial effluent turbidities during the filter ripening may consume some of the added chlorine disinfectant and hence result in an increased chlorine demand. As a result, there is a need for a mandatory filter-to-waste procedure.

Since complete elimination of filter-to-waste procedure is undesirable, minimizing the duration of the filter ripening and improving instantaneous effluent quality becomes important. This in-turn would benefit from optimization of the filter ripening sequence (FRS) in term of operating parameters such as filtration rate and influent turbidity. For optimization, the factors affecting the filter ripening must be identified. Characterization of the filter ripening sequence is also important for plant optimization.

5.1.1 Filter Ripening Sequence

Amirtharajah and Wetstein (1980) conducted a series of filtration experiments in a pilot scale and showed that the initial effluent quality from a filter used over several filter runs could be divided into three segments: (i) the lag period due to the clear backwash water remaining in the underdrain system up to the bottom of the filter media; (ii) the rising limb, culminating in two turbidity peaks, due to particles detached during collisions of the settling media at the end of the backwash; and (iii) the long receding limb due to dispersion and mixing of the media-revived particles from the filter with the influent and the accumulation of influent particles within the media pores.

Francois and Van Haute (1985) suggested that the peak turbidity was more related to the influent water (approximately 95 % of the time) than to the remnant water as previously proposed. They also explained that the ripening period of the filter coincides with a change in pore structure of the bed. The initial turbidity breakthrough was related to the breakdown of the initially placed weak hydroxide flocs within the pores of the media due to the rapid increase of velocity gradients as particles begin to accumulate. The loosely deposited flocs are scoured back into the suspension by the increased shear. Because of an inadequate pore structure and the passage of the initial weak flocs through the filter media, the primary peak of effluent turbidity would occur. They also found the overdosing the primary coagulant at the beginning of a filter run decreased the ripening peak and shortened the time for it to occur. This was attributed to an increased blocking rate of the pores and dead zones. The rate of pore blocking was suggested to be strongly influenced by the chemical treatment of water.

Payatakes et al. (1981) and O'Melia and Ali (1978) indicated that the improving phase of the filter ripening was due to the accumulation of particles within the media flow channels. Payatakes et al. (1981) used visual data to show that the main mechanism causing alteration of the geometry of the flow channels within the filter media was "throat clogging". O'Melia and Ali (1978), by using a polymer coagulant system, mathematically related the improving phase of filtration to accumulation of particles and the formation of dendrites and particle chains within the media pores. The constantly accumulating particles within the media were thought to continuously improve the effluent quality by the improved capture of influent particles by dendrites. Mathematical models of filtration were developed to incorporate the filter ripening period. However, their usage was limited due to insufficient understanding and their complexity.

Amirtharajah and Wetstein's (1980) theory was later modified by Cranston (1987). The three stages of the FRS were defined as: i) the remnant stage; ii) the influent mixing and particle stabilization stage; and iii) the filter media conditioning stage. The remnant stage was associated with the backwash water remaining within the underdrains, the media and above the media after backwash. A possibility for a peak turbidity exists in the remnant stage due to particles sheared off media at the beginning of the filtration cycle, or at the end of the backwash, as the filter media particles collide with each other. The influent mixing and particle stabilization stage occurs as the influent water disperses into the coagulant free remnant backwash water above the filter media. The large peak was feasible in this stage due to particle stabilization of the previously destabilized influent particles as they interact with the non-coagulated backwash water which has been coagulated and filtered. The media conditioning stage was characterized by the accumulation of particles within the filter media and an increased efficiency of particle removal.

5.1.2 Filter Ripening Sequence Reduction Techniques

Reduction of the FRS will lead to energy conservation, water savings and reduced risk of microbial contamination. Several methods have been examined to reduce or remove the period of initial poor quality effluent from filters. The two major methods identified were implementing a rate controlled start and coagulant addition to the backwash water (Cranston and Amirtharajah, 1987). The FRS was reduced by controlling the filtration rate during ripening, i.e., the filter unit was started at a low filtration rate and gradually increased to full flow after the FRS was completed, which was referred to as the 'slow-start' method (Amirtharajah and Wetstein, 1980). The term 'slow-start' as referred to in the literature does not always refer to slower ripening rates compared to the normal filtration rates but a different filtration rate to reduce FRS and to conserve water. However, suitable filtration rates for 'slow-start' were not well researched. Determination of appropriate initial filtration rates for rate controlled ripening requires optimization to achieve economical and quality filter operations.

The use of coagulants in backwash water has been shown to improve the initial effluent quality, with the optimum coagulant type being alum or the primary coagulant used in the preceding treatment (Cranston and Amirtharajah, 1987). Studies conducted by Harris (1970), Cranston (1987) and Yapajakis (1982) indicated that the addition of polymer to the backwash water served to minimize the filter ripening duration and magnitude under both pilot and full scale plant conditions. Experimental evidence suggested that adding polymer to the initial influent may also effectively reduce the ripening stage (Francois and Van Haute, 1985). Coagulant addition to influent primarily influenced the FRS in terms of adjusting the quality of the influent particles and their eventual capture in the filter bed. However, particle capture was mainly influenced by filter hydraulics, i.e., filtration rates. The coagulant addition to the backwash water was considered as a pre-conditioning step by the adsorption of the coagulant to the filter media (Harris, 1970). Therefore, optimization of filtration rates was beneficial even with the use of a polymer in the backwash or initial influent to minimize the FRS duration and reduce the risk of poor quality effluent.

5.2 Study Objectives

By investigating the factors affecting the FRS such as influent turbidity, filtration rate, temperature, duration of backwash and effluent control mode, optimum ripening conditions in terms of the above factors could be established. One of the parameters overlooked in the filter ripening research is the influent solid flux rate, which is the product of influent solids concentration (indirectly measured by turbidity) and filtration rate. Optimization of the influent solid flux rate will result in combined optimization of the filtration rate and influent turbidity. Optimizing such parameters, i.e., filtration rate during the FRS (by adjusting effluent valves), or optimizing influent turbidity (by adjusting the pretreatment, or polymer addition to the influent), or a combination of both to optimize the influent solid flux rate would lead to more economical filter operations by reducing the FRS.

This study examined the effects of media type (crushed quartz mono-media, anthracite/round sand dual-media and a conventional filter sand), filtration rate (3 to 14 m/h), influent turbidity (2 to 6 NTU), influent solid flux rate, backwash duration (3 to 15 minutes), filter effluent control (constant rate and declining rate) and temperature (6 to 19 °C) on the FRS as part of the on-going study of filtration at the Rossdale water treatment plant in Edmonton, Canada. The first part of the study evaluated the effects of such parameters in constant rate filter ripening and the second part involved the use of declining rate filtration. The FRS was characterized by the lag time, the peak turbidities and their time of occurrence, the FRS duration and the solid flux released to the effluent during the FRS. The results helped to determine the time requirements, effluent quality and optimization of the FRS to minimize the wasting of water and ensure a good quality filtered water.

5.3 Definition of the FRS End

Experience in some full scale plants (Cleasby et al. 1989) suggest that the conclusion of the ripening period was assumed when the effluent turbidity drops to 0.2 to 0.3 NTU. McDonald (1995) suggested that a finished water turbidity of 0.1 to 0.2 NTU would minimize the health risk posed by *Cryptosporidium*. At the Rossdale water treatment plant, the end of the ripening sequence is defined as the time when the initial effluent turbidity drops to 0.1 NTU, after the occurrence of all possible peaks. This definition is not efficient in describing the end of ripening where the filter bed becomes matured to provide effective filtration. Using such turbidity limits for defining the end of filter ripening rely on the fact that the filter bed becomes mature at such turbidity. However, even if the effluent turbidity is below the desired limit of the end of FRS, surges in the influent may cause effluent turbidity spikes. Therefore, there exists a risk of inferior effluent quality if the end of FRS is considered as the moment when the effluent turbidity reaches a specified value. To minimize such risk, the end of FRS must be defined by the characteristics of the FRS turbidity profile. This can be used for modeling and comparison purposes of this study. Such definition for the end of the FRS is not well documented in the literature. Therefore, based on the shape of the effluent turbidity profile during FRS, end of the FRS was assumed to be the point of change from rapid effluent improvement to slow effluent improvement after the peak turbidity of the FRS profile. A conservative graphical construction for the end of the FRS is based on the bisection of the angle formed by the two tangents to the straight line portions of the receding limb and the normal operating turbidity curve, the intersection of the bisection and the FRS curve defining the end of the FRS (Figure 5.1). In practical terms, it can be expressed as the point where a significant change in the reduction rate of effluent turbidity ends, beyond which the rate becomes similar to normal filtration values, i.e., the filter bed becomes matured. The duration of the FRS (t_m) is measured as the time difference between the start and end of the FRS as defined above.

5.4 Effluent Solid Flux During the FRS

Based on solids removal, the peak turbidities have been considered in defining the FRS utilizing the fact that turbidity is an excellent indication of effluent contamination. Though the turbidity is decreasing at the later stages of FRS, the immature state of the filter bed may give passage to microorganism. Therefore, the total amount of solids flushed through a filter during the FRS can also be effectively used to describe such risks. Therefore, a term, denoting the FRS flux (F_m) is defined as, "mass released to the effluent during the FRS per unit area" (for a duration of t_m). The amount of material (F_m) flushed through the filter during ripening indicates the impurities released to the effluent. The smaller the flux less the risk of contamination. This can also be used to evaluate the differences in operating modes (Constant rate, Declining rate), whether the same flux occurs during the FRS regardless of the characteristics of the FRS curve. A mathematical expression for F_m can be derived.

Effluent solids flux during the time interval dt

$$df_m = C'_t \bullet v_t \bullet dt \qquad [5.1]$$

Where, units of df_m is g/(m^2 filter area), C'_t and v_t are the solids concentration (g/m^3) and the filtration rate (m^3/m^2/h) at time t.

Therefore, total mass released per m^2 filter area during the FRS is given by:

$$F_m = \int f_m = \int_0^{t_m} C'_t \, v_t dt \qquad [5.2]$$

In constant rate filtration, v_t is constant (v). Therefore,

$$F_m = v \bullet \text{Area under the FRS curve in time } t_m \qquad [5.3]$$

In declining rate filtration (DRF), however, during the FRS, the filtration rate decreases as filtration progresses. Therefore, the ripening period is divided into small increments (6 seconds interval, as the data were collected) until the end of ripening Equation 5.1 can be modified to calculate the DRF ripening flux as:

$$F_m = \sum_{n=1}^{z} (t_{n+1} - t_n) \bullet \left(\frac{C'_n + C'_{n+1}}{2} \right) \bullet \left(\frac{v_n + v_{n+1}}{2} \right) \qquad [5.4]$$

Where, $n = z$ when $t = t_m$.

McCoy and Olson (1986) found that the particle counts and turbidity were directly proportional but no clear relationship could be obtained with bacteriological counts. The solids concentration (C') can be assumed proportional to the nephilometric turbidity units (c), where,

$$C' = k \bullet c \qquad [5.5]$$

In this study, indirect solids concentrations were established from the turbidity values. Considering the comparative nature of study, this assumption should not influence the results.

5.5 Pilot Plant Operations

The first part of the ripening studies was conducted in a filtration pilot plant with six columns as part of a broad study to select a new filter media for the Rossdale water treatment plant (Suthaker et al. 1995a and 1995b). Three filter columns contained anthracite/sand dual-media, two columns contained crushed quartz and one contained the existing conventional filter sand (See Table 5.1). The filters were operated at 3.5 m/h, 8 m/h and 11 m/h. Pilot columns were tested for backwash durations of 3, 5, and 10 minutes. The turbidity of the filter influent during the study portion completed remained within 2 to 10 NTU. The temperature remained 19°C during this portion of the study. Headloss across filter media was recorded manually. Backwash water pressure, duration of air scour and media expansion were maintained similar during filter backwash. Effluent turbidity was recorded automatically by a data logger every 6 seconds for a time span of 100 minutes or until the turbidity dropped well below 0.1 NTU. This was considered as in-plant effluent turbidity guideline for the FRS end. From the constant rate filter ripening study, the effects of filtration rate, media type and backwash duration were obtained.

As a result of the media selection study (Suthaker et al. 1995 a, 1995b), crushed quartz filter media was chosen for further investigation in declining rate filtration. The constant rate pilot plant was then converted into declining rate filtration (Figure 5.2). Effluent weir control was employed for the filter control. Such control was achieved by using the built-in weir inside the turbidimeter. The effluent valves were preset to a filtration rate and remained untouched during the experiment at that flow condition. The filtration rates studied varied from 4 to 14 m/h. The influent turbidity ranged from 2 to 9 NTU. All filters were backwashed for a duration of 15 minutes to ensure adequate backwashing. The water temperatures ranged from 6 to 19°C.

The FRS curves were obtained for each combination of study parameters. Ripening data were collected over a year of pilot plant operations incorporating seasonal changes of influent turbidity and water temperature which cannot be controlled in the pilot plant. Due to lack of control over influent turbidity and water temperature, some combinations of study parameters could not be studied, however, the data collected were sufficient to draw conclusions from this study. From the available database, constant rate and declining rate FRS were compared. From the FRS curves: i) the lag period (t_l), time to reach the two peaks and the FRS end (t_{p1}, t_{p2}, t_m); ii) turbidities at peaks (c_{p1}, c_{p2}) and at the FRS end (c_m); and iii) the solid flux through the FRS (F_m), as defined earlier could be determined. Figure 5.1 depicts the above properties of the FRS curve. Graphical evaluations were used to determine the optimum ripening conditions.

5.6 Summary of Results

The database was sorted accordingly to study the effect of an individual variable while other variables remain the same. Optimization was carried out by minimizing the turbidity, time and flux parameters at the FRS peaks and end as depicted in Figure 5.1. In this manner, independent effects without any interaction effect from other variables can be studied.

The effects of backwash duration were felt on the flux at the FRS end (Figure 5.3) which indicated that more than 5 minutes of backwash is required to ensure proper backwashing of the filters of this pilot plant. A similar trend was seen for the time of the FRS end. All the other parameters under investigation were not influenced by the duration of backwash. This suggests that a backwash duration of 5 minutes or more is required in this pilot plant to eliminate the effects of backwash duration. In the following analysis, the data for which the pilot plant was backwashed for more than five minutes were considered in order to eliminate the minor effect of backwash duration.

5.6 1 Optimization of Variables

Early work by Amirtharajah and Wetstein (1980) suggested that the peak turbidity was represented by a parabolic curve against the filtration rate. This was the only indication available in the literature that the filtration rates can be optimized to reduce the FRS. Though many variables are found to influence the FRS, all variables cannot be optimized for efficient filter ripening procedure. The filtration rate at which filter can be ripened can easily be optimized and then changed to operating rates (as a 'slow-start', together with filter-to-waste procedure). The other options demonstrated in the literature for the FRS reduction such as polymer addition may further optimize the turbidity conditions of the influent and backwash remnants. Filter influent turbidity can be optimized to some extent utilizing the pretreatment facilities of a water treatment plant or by adding polymer as preconditioning. Optimization of these two variables will take care of the influent solid flux rate which is the product of those variables. Optimizing water temperature is not a viable option in most water treatment plants. Optimization of backwash duration from a pilot plant study could not be scaled-up as it involves different mixing and hydraulic conditions.

5.6.1.1 Optimization of Filtration Rates

The effect of filtration rates on the time of FRS end is shown in Figure 5.4. The effects of filtration rates on the time to reach the two peaks and the FRS lag time posed similar trends as in Figure 5.4. It was generally observed that the above times decreased with the increase in filtration rates, however, the decrease was much greater at filtration rates less than 8 m/h. Increased filtration can flush the backwash remnants quicker to produce shorter FRS lag time. However, the differences in FRS lag time with increased filtration rates were very small compared to the FRS duration. The FRS flux increased with the filtration rate but the rate of increase is more after 8 m/h (Figure 5.5). Similar effects were seen for the turbidity at the FRS end. The first turbidity peak was not influenced by the filtration rate (Figure 5.6), however, the second peak was affected by the filtration rate. A rapid increase of the second peak turbidity was experienced after 8 m/h filtration rate (except for the fluctuations in the data at lower temperatures). This was also experienced in a previous study (Amirtharajah and Wetstein,1980).

Time taken for the FRS end also characterizes the quantity of water wasted during ripening and the time a filter is out of service (filter-to-waste). If a filter-to-waste procedure is adopted, then the plant operator will be less concerned about the peak turbidities and associated microbial risks since the effluent does not enter the processed water. The major concern is then the quantity of water wasted during filter ripening and the time a filter is out of service. For the treatment plants which has a small number of filters, FRS duration can be very important to meet the water demand. The results of this study show that ripening at more than 8 m/h will not substantially improve FRS duration (Figures 5.4 and 5.5). If a treatment plant has many filters and the time a filter is out of service is not a great concern, minimizing the volume of water wasted during ripening is the goal which will result in water and energy conservation.

Figure 5.7 and Table 5.2 show the volume of water wasted during filter ripening (V_w) at different filtration rates for a 'slow-start' in DRF. Results indicate that the temperature plays an important role in the optimum filtration rates. At cold waters (6°C), increasing the filtration rate did not significantly increase V_w. In warm waters, substantial effect of filtration rates on V_w was experienced denoting the existence of an optimum filtration rate to minimize Vw. In constant rate filtration, though FRS duration decreased with higher filtration rate (large decrease from 4 to 8 m/h and then small decrease), V_w was minimum at 8 m/h for anthracite/sand (Table 5.2). For crushed quartz, 18 percent of water was conserved by ripening at 8 m/h compared to 4 m/h. No significant change is evident at filtration rates higher than 8 m/h for crushed quartz. The results suggest that ripening the filter at 8 m/h will help conserve water. Treatment plants should also look at the water and energy costs associated with filter-to-waste at higher filtration rates. The results show that the filtration rate for a 'slow-start' can be optimized with the help of pilot plant studies to match the individual plant operating conditions.

Filtration rates govern the transport, attachment and the detachment of particles within the media. Increased filtration rates enhance the transport of particles to the sites within the interstitial pores of the filter bed for removal by attachment to the filter media. Increased filtration rates also favor the shear detachment of previously attached particle from the media which is released to the effluent or eventually captured at the bottom portion of the filter bed (Ginn et al. 1992).The above filtration mechanisms, associated with the filtration rates may be used to explain the change in trend of filtration rate effects on the time parameters of the FRS curve. At low filtration rates, the lesser particle transport and detachment tend to clog the top portion of the filter bed. Advancement of the clogging front in the filter bed will be also slower, resulting in longer time for the ripening peaks to occur and the filter ripening to end. As the filtration rate increases, the above phenomenon occurs more rapidly, resulting in quicker filter ripening. After 8 m/h, the shear detachment may have dominated the transport and attachment to release more particles in the effluent and hence the advantage of the increased filtration rate was lost for a quicker ripening of filters. This concept is also validated by the rapid increase of the FRS flux (Figure 5.5) and turbidity at the FRS end (similar trend as in Figure 5.5) after the 8 m/h filtration rate.

5.6.1.2 Optimization of Influent Turbidity

Influent turbidity can affect the FRS by the amount of influent particles transported to the filters. Time to reach the second peak was minimized when the influent turbidity is between 3.5 and 5 NTU for crushed quartz media but increased with the influent turbidity for the anthracite/sand dual-media (Figure 5.8). No effect of influent turbidity was evident from Figure 5.9, which depicts its effects on the FRS flux. A similar trend, as shown in Figure 5.9, was observed for all other parameters except for t_{P2} which shows a slight decrease with higher influent turbidity. Therefore, direct optimization using the effects of the influent turbidity is not possible in terms of the FRS reduction. The results can be used to make additional conclusions from Figure 5.4 (t_m) and Figure 5.5 (F_m) which depicts the combined effects of influent turbidity and temperature in addition to the filtration rate. The lack of influence of influent turbidity on the above three parameters suggest that the effects seen in those figures are caused by the temperature variations which will be discussed later.

5.6.1.3 Optimization of Influent Solid Flux Rate

In constant rate filtration (CRF) ripening, effects of the influent solid flux rate on turbidities at the two peaks and at the FRS end were similar to the trend observed for c_{P1} as shown in Figure 5.10. For F_i values between 20 and 35 NTU•m^3/(m^2•h), above parameters were the lowest. A slight increase of c_{P1} was observed for declining rate filtration (DRF) with increased F_i (Figure 5.11). In DRF, rapid increases in the above parameters were observed when F_i was greater than 35 NTU•m^3/(m^2•h) (Figure 5.12, shown for C_m), especially in cold water. However, such effects were less in warm water. When F_i was greater than 30 NTU•m^3/(m^2•h), rapid reduction of t_l was observed in CRF (Figure 5.13).

The time of the FRS end was not affected by F_i except for high temperatures (19°C) where large reduction of t_m (50 percent) was observed with increased F_i from 10 to 40 NTU•m^3/(m^2•h) in DRF (Figure 5.14). Time for the first peak decreased with increased F_i (Figure 5.15) in DRF. Similar results were also observed for CRF operations. Time of the second peak was not affected by F_i except at 19°C, a sudden drop from 25 to 10 minutes in t_{P2} was experienced for F_i increase from 5 to 20 NTU•m^3/(m^2•h) in DRF. This suggests that effects of F_i on the time characteristics of the FRS was felt more at high temperatures. The influent solid flux rate did not influence the volume of water wasted (V_w). Therefore, it is beneficial to keep the influent solid flux rate in the range of 20 to 35 NTU•m^3/(m^2•h). It is evident from the results that the influent solid flux rate was more influential than the influent turbidity. In practical terms, the effect of the interaction between the filtration rate and the influent turbidity is more important than the influent turbidity alone. Therefore, optimizing the FRS in terms of the influent solid flux rate instead of influent turbidity should be appropriate. This can be achieved by adjusting the filtration rate according to the influent turbidity.

5.6.2 Effect of Media Type, Temperature

Figure 5.16 depicts the variation of the FRS flux. A similar trend was observed for the turbidity at the FRS end. Crushed quartz provided the lowest FRS flux and turbidity at the end of FRS among the media tested (Figure 5.16), but it took a longer time to mature at 4 m/h, at which the existing media quickly matured (Figure 5.17). However, the existing media took the longest time to mature at 8 m/h. At 11 m/h, the differences were not significant. The effluent turbidity at maturation was the lowest for crushed quartz and largest for the anthracite/sand dual media. Though, lag time was affected by the media type, the differences were not substantial. The times of the peaks were retarded in crushed quartz than the other media types except for the existing media which is approximately equal with crushed quartz. Crushed quartz also produced the lowest peak turbidities (Figure 5.18). In view of quality and the risk of microbial contamination, crushed quartz would be a better choice than the other media. Though some t_m values shown in Table 5.2 are similar in both anthracite/sand and crushed quartz media, water wasted during ripening is different. At high filtration rates (11 m/h), approximately six percent of water can be saved with the use of crushed quartz.

Figure 5.19 shows the effect of temperature on the FRS curve. The only visible effect of higher temperature was the lower peak turbidities and hence the FRS flux. Additional conclusions about temperature effects can be made from Figure 5.5 (F_m), and Figure 5.7 (V_w) which depicts the combined effects of influent turbidity and temperature in addition to the filtration rate. Since the effect of influent turbidity on the above parameters have been ruled out (section 5.6.1.2), the effects seen in Figures 5.4 to 5.7 could be attributed to the temperature changes.

5.6.3 Declining vs. Constant Rate Filtration

By combining the databases for constant rate filtration (CRF) and declining rate filtration (DRF) for crushed quartz filter media, the effect of filter effluent control (constant or declining rate) was examined at 0.05 significance level. The results indicated that the effluent control method was influential on the FRS flux, time of the FRS end and time for the first peak to appear. Figure 5.20 depicts some direct comparisons of the FRS curves in CRF and DRF at different filtration rates. Though differences were observed in peak turbidities at 11 m/h filtration rate, it should be noted that the differences are small in view of the lowest peak turbidities in crushed quartz compared to the other media types. Quicker ripening was observed in CRF. The FRS flux was also lower in CRF. Hutchison and Foley (1974) suggested from direct filtration studies that DRF would have an advantage of lower shear force on floc particles attached to the media due to declining flow rate. The floc deposition in DRF would take place in areas within the filter not ordinarily occupied during CRF. DRF flow profiles in this study suggest that the filtration rate decrease was very small during the period of ripening. Therefore the decrease of shear force on floc particles attached to the media was also very small. In order to explain the differences observed between DRF and CRF (mainly the end of the FRS), the flow pattern associated with the rate control mechanism may be helpful. In DRF, the effluent control method allows the flow to decline naturally in conjunction with the water level increase. In CRF, the effluent control (valves) regulates to compensate for the lost flow due to headloss developed within the media. Such valve regulations may propagate minor surges upstream which may cause floc detachment, eventual release and reattachment which could quickly mature the filter bed. In view of the filter-to-waste procedure, CRF would be preferable due to quicker ripening.

5.6.4 Number of Turbidity Peaks in Filter Ripening

All the FRS curves contained two turbidity peaks in DRF and contained one or two peaks in CRF. The FRS with one peak may suggest simultaneous occurrence of both peaks or non-existence of one peak. Under rare circumstances, more than two peaks appeared, especially, in the existing filter media. It was found that the maximum of the first two peaks was not always at the second peak, as indicated in the literature (Bucklin et al. 1988). This observation suggests a major influence by both the remnant stage and the influent mixing/particle destabilization stage defined by Cranston (1987).

5.7 Conclusions

The ripening curve was earlier characterized by the turbidities and the time to reach the peaks and the end of the filter ripening for the purpose of analysis and optimization. In addition, the cumulative solids released to the effluent during the filter ripening period is also important in defining the filter ripening characteristics. The end of the filter ripening can be defined as the instant where a significant change in the effluent turbidity reduction rate occurs, beyond which such rate becomes similar to normal filtration values. The influent solid flux rate to the filter, which is the product of filtration rate and influent concentration, is also a key factor in the filter ripening in addition to the filtration rate, influent turbidity, media type and temperature.

Conclusions about the influence of operating parameters on the filter ripening characteristics can be drawn. Filtration rate generally governs the time related characteristics of the ripening curve. The influent solid flux rate influenced the turbidity parameters more than the influent turbidity. Warm waters tend to produce better ripening conditions compared to cold water. Quicker ripening, lower FRS flux and higher peak turbidities were observed in CRF when compared to DRF. Crushed quartz also produced the lowest peak turbidities among the media studied. In view of quality and the risk of microbial contamination, crushed quartz would be a better choice than the other media types tested.

Based on this study, optimization of some filter operating parameters were possible. Water wasted during ripening can be minimized by selecting a suitable filtration rate for ripening. A filtration rate of 8 m/h for a 'slow-start' is the optimum for reducing the filter ripening sequence and for minimizing the quantity of water wasted during ripening for constant and declining rate filter operations. This can be used in conjunction with filter-to-waste procedure and coagulant addition to backwash. Once the filter ripening is over, the filtration rate can be slowly adjusted to the operating rates. The existence of the optimum filtration rate depends on the particle transport and shear detachment aspects, whichever dominates at a given filtration rate. Influent turbidity did not directly influence filter ripening but indirectly, through its interaction with the filtration rate (influent solid flux rate). The optimum influent solid flux rate was found to be between 20 to 35 $\mathrm{NTU \cdot m^3/(m^2 \cdot h)}$. This can be achieved in treatment plants by adjusting the filtration rate.

5.8 Notations

CRF : constant rate filtration

DRF : declining rate filtration

C' : solids concentration (g/m^3)

c : turbidity (NTU)

c_m : effluent turbidity at the FRS end (NTU)

c_{P1} : effluent turbidity at the first peak (NTU)

c_{P2} : effluent turbidity at the second peak (NTU)

F_i : influent solid flux rate ($[\mathrm{NTU \cdot m^3}]/[\mathrm{h \cdot m^2}]$)

F_m : effluent solid flux during the FRS ([NTU•m^3]/m^2)

FRS : filter ripening sequence

k : constant relating turbidity (NTU) and solids concentration as in equation 4 (g/[m^3•NTU])

t_l : lag time of the FRS (min)

t_{P1} : time to reach the first peak (min)

t_{P2} : time to reach the second peak (min)

t_m : FRS duration (min)

v : filtration rate (m^3/[h•m^2])

V_w : Volume of water wasted during ripening (m^3/m^2 filter area)

Subscripts:

i : influent

m : the FRS end

P1 : first peak

P2 : second peak

t : time

5.9 References

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Table 5.1 Characteristics of Filter Media

Filter media	Effective Size (mm)	Uniformity Coefficient
Existing media	0.61	1.34
Crushed Quartz	0.50	1.52
Round Sand	0.46	1.59
Anthracite	0.89	1.55

Table 5.2 Comparison of the ripening time and the volume of water wasted in CRF[1]

	Anthracite/Sand[2]		Crushed Quartz[2]	
Flowrate m/h	t_m min	V_w m^3/m^2 area	t_m min	V_w m^3/m^2 area
4	40	2.67 (14) [2]	41	2.73 (18) [2]
8	17.5	2.33	17.3	2.31
11	13.3	2.44 (5) [2]	12.5	2.29 (-1) [2]

[1] at 19°C, influent turbidity = 4 NTU.

[2] values in parentheses indicate the percent increase in water wasted when compared to 8 m/h flowrate

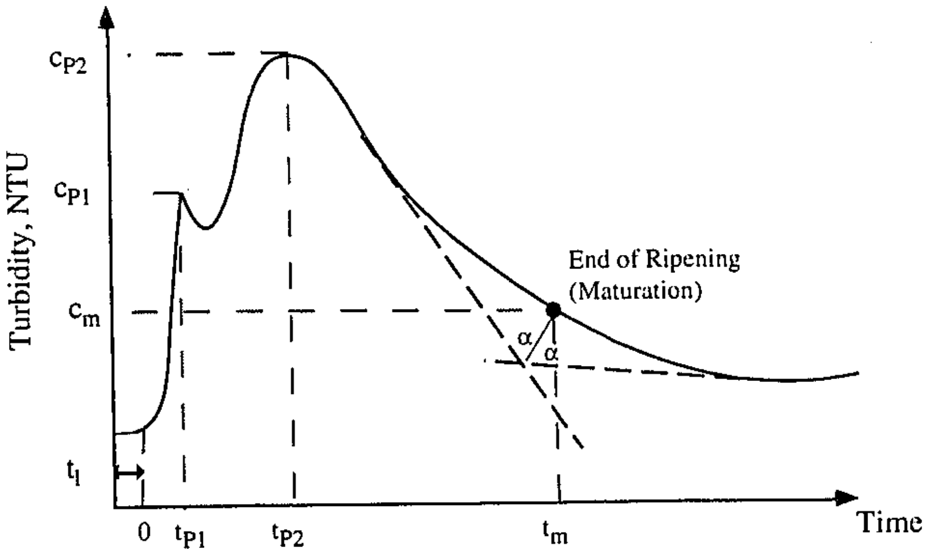

Figure 5.1 Characteristics of Filter Ripening Curve

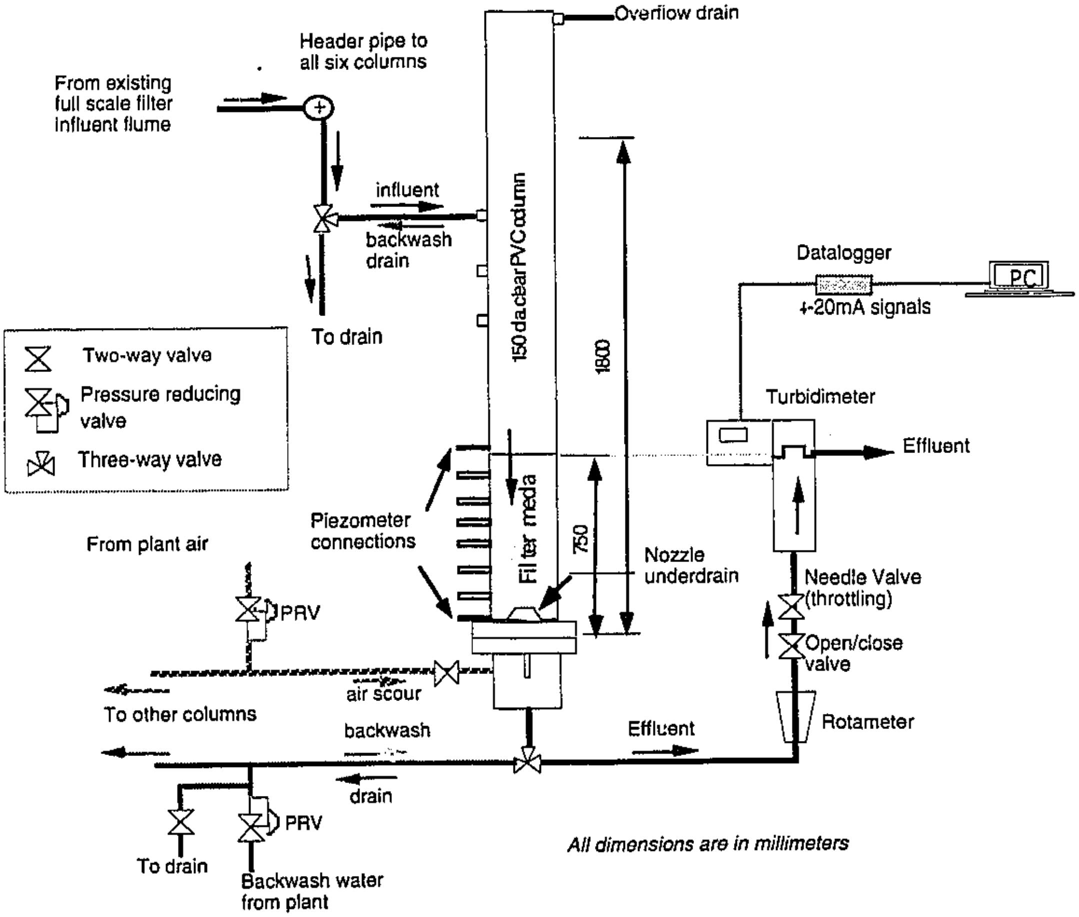

Figure 5.2 Schematic of Pilot Plant for Declining Rate Filtration

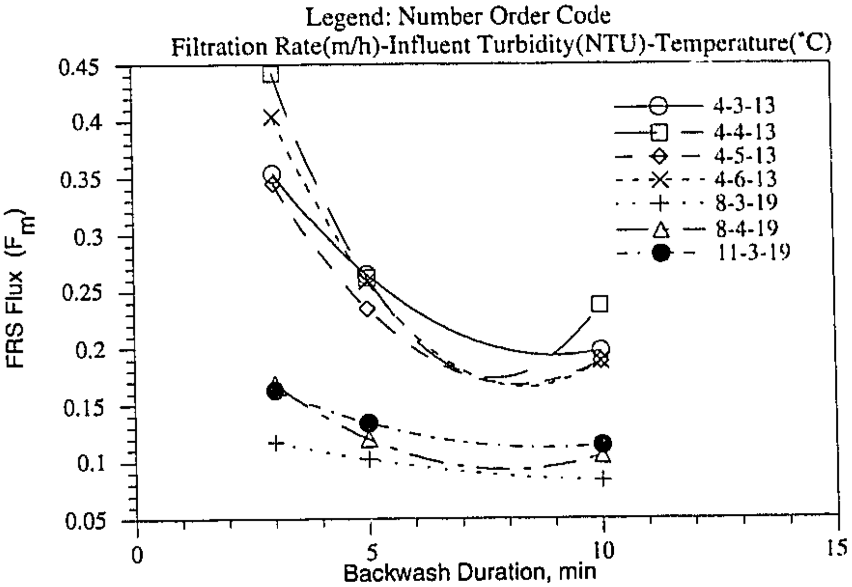

Figure 5.3 Effects of Backwash Duration on the FRS Flux

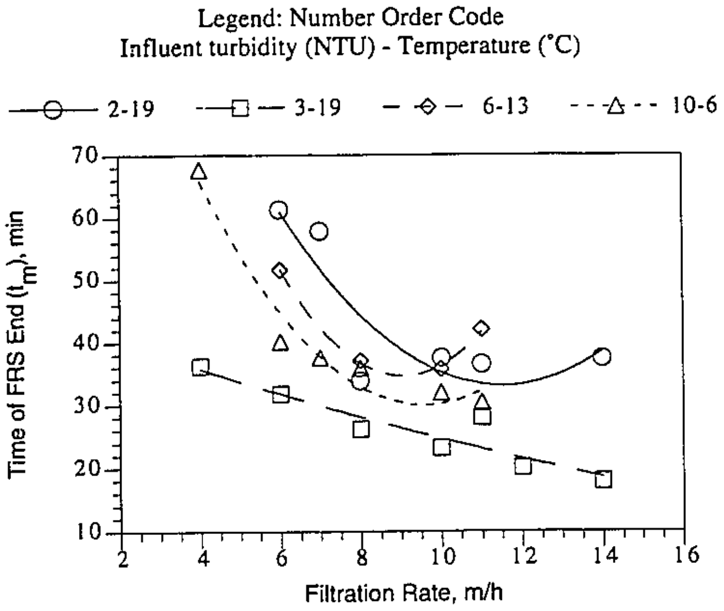

Figure 5.4. Effects of Filtration Rate on time of FRS end for DRF, Crushed Quartz media

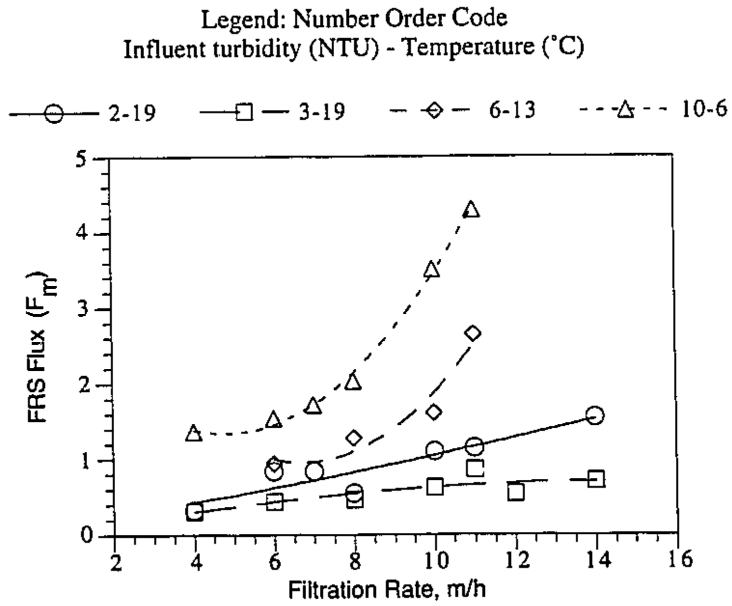

Figure 5.5. Effects of Filtration Rate on FRS Flux for DRF, Crushed Quartz media

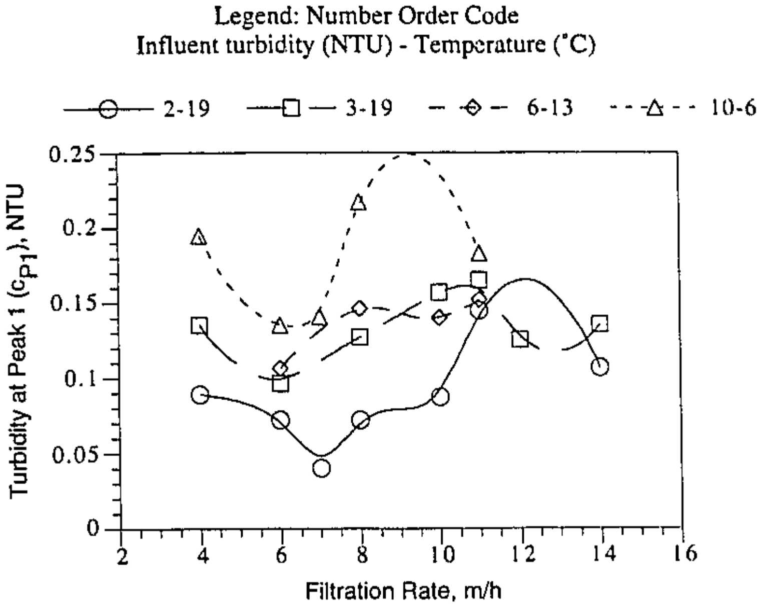

Figure 5.6. Effects of Filtration Rate on Turbidity at Peak 1 for DRF, Crushed Quartz media

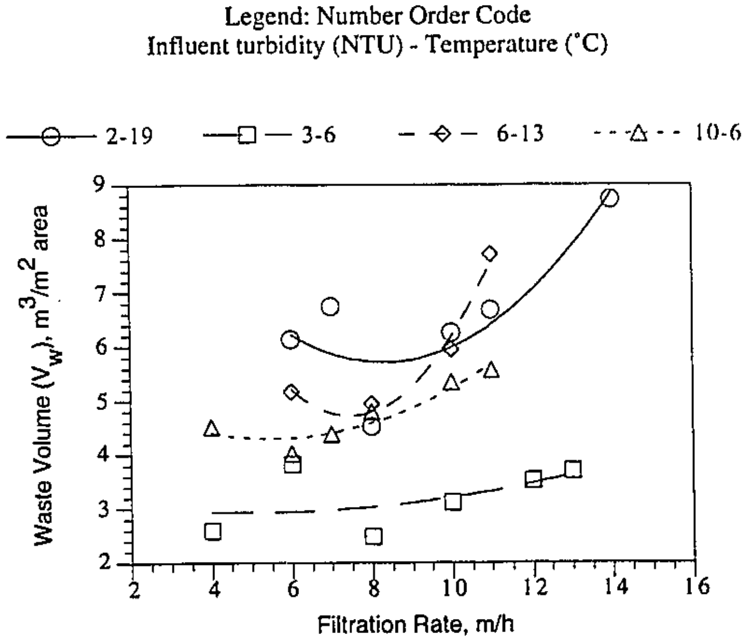

Figure 5.7. Effects of Filtration Rate on the Volume of Water Wasted, for DRF, Crushed Quartz media

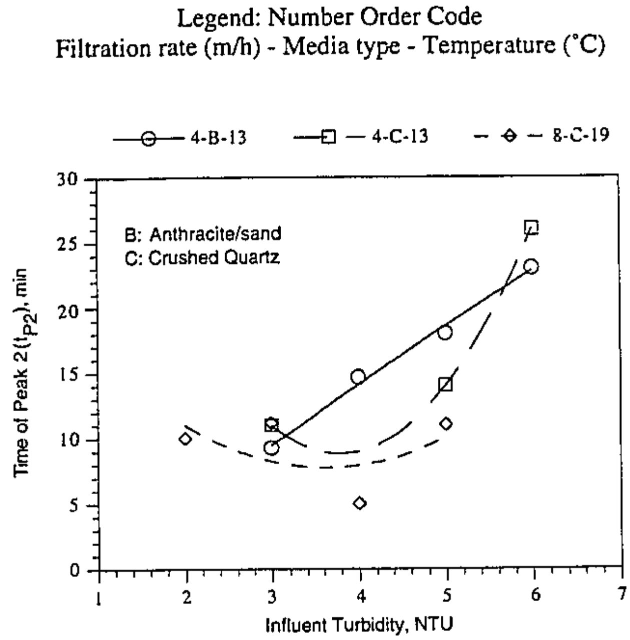

Figure 5.8. Effects of Influent Turbidity on Time of Peak 2 for CRF

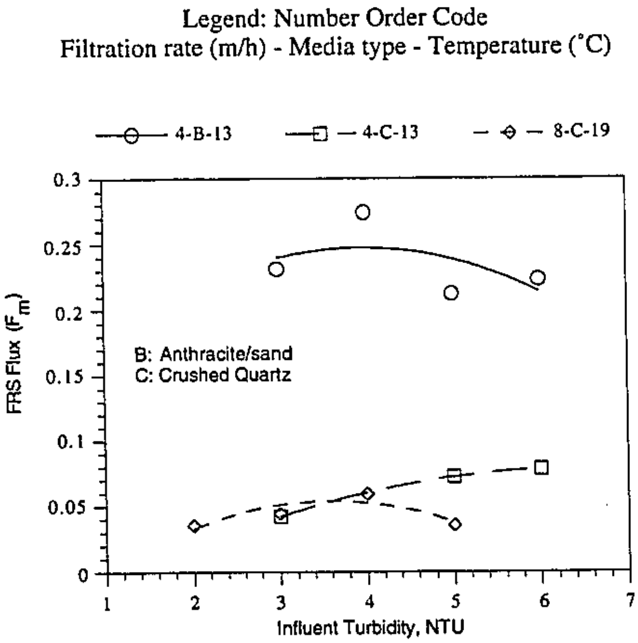

Figure 5.9. Effects of Influent Turbidity on FRS Flux for CRF

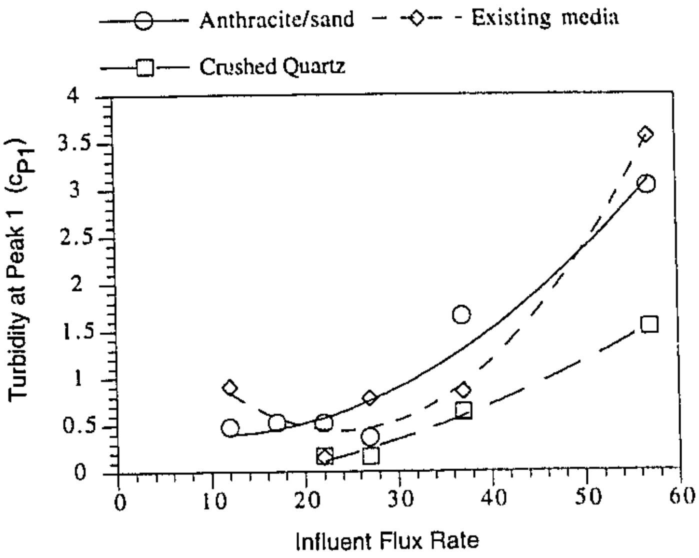

Figure 5.10. Effects of Influent Solid Flux on Turbidity at Peak 1 for CRF for Various Filter Media

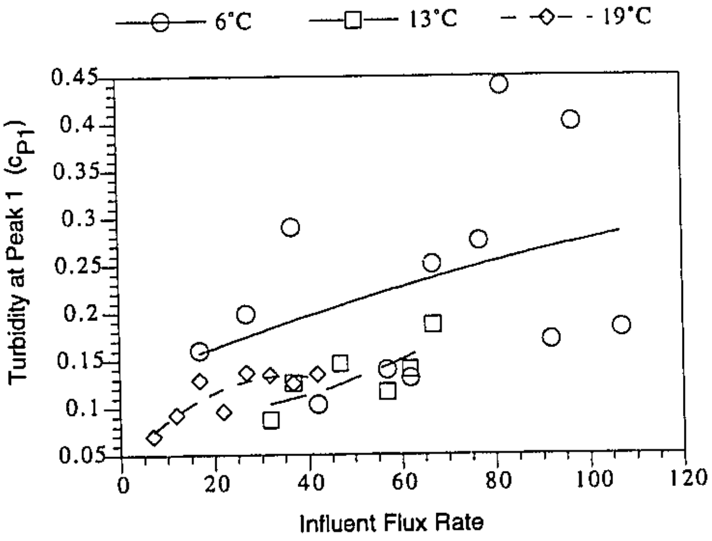

Figure 5.11. Effects of Influent Solid Flux on Turbidity at Peak 1 for DRF, Crushed Quartz media for Various Temperatures

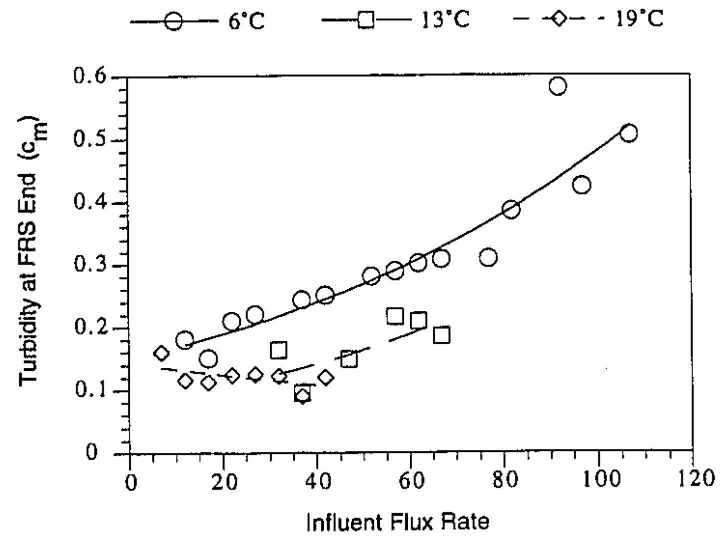

Figure 5.12. Effects of Influent Solid Flux on Turbidity at FRS End for DRF, Crushed Quartz media for Various Temperatures

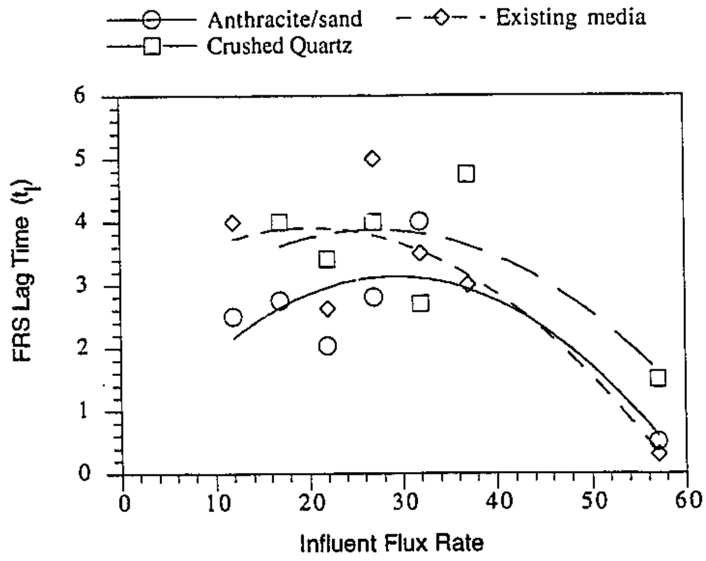

Figure 5.13. Effects of Influent Solid Flux on the FRS Lag Time for CRF for Various Filter Media

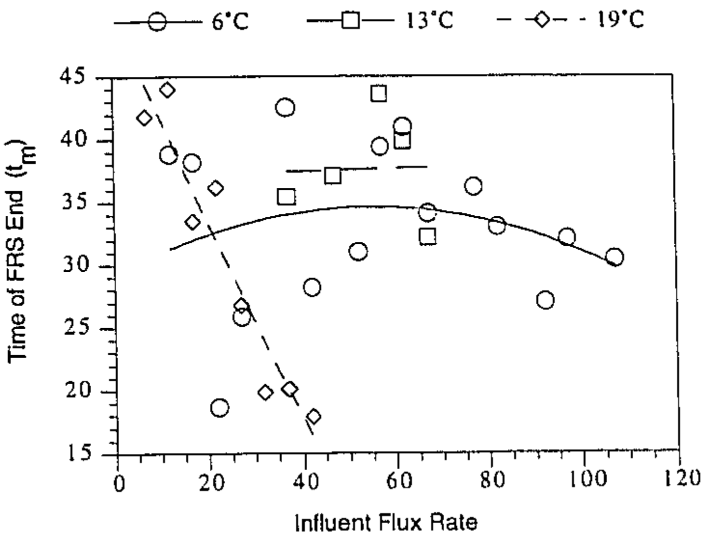

Figure 5.14. Effects of Influent Solid Flux on time of FRS end for DRF, Crushed Quartz media for Various Temperatures

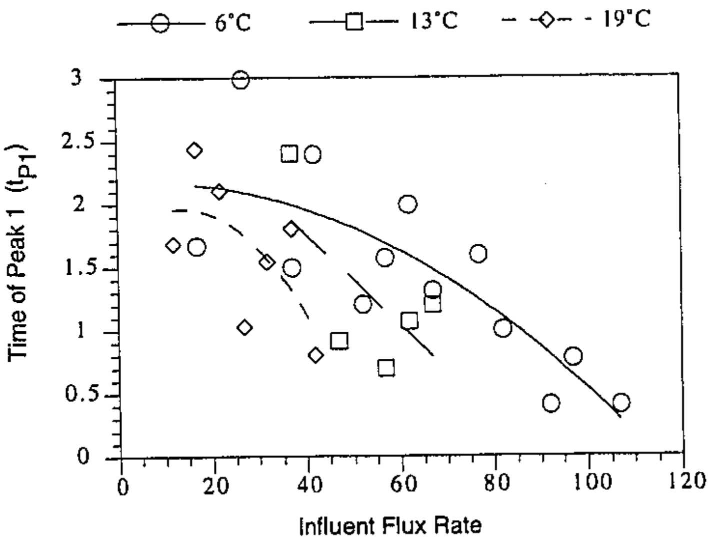

Figure 5.15. Effects of Influent Solid Flux on time of Peak 1 for DRF, Crushed Quartz Media for Various Temperatures

Legend: Number Order Code
Filtration rate (m/h) - Temperature (°C) - Influent Turbidity (NTU)

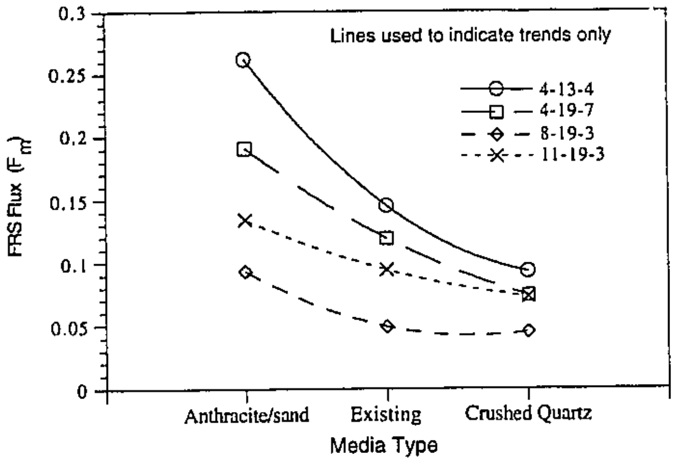

Figure 5.16. Effects of Media Type on FRS Flux for CRF

Legend: Number Order Code
Filtration rate (m/h) - Temperature (°C) - Influent Turbidity (NTU)

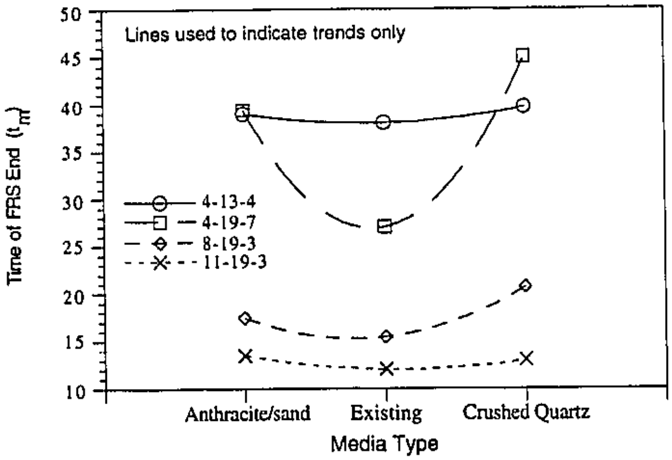

Figure 5.17. Effects of Media Type on time of FRS end for CRF

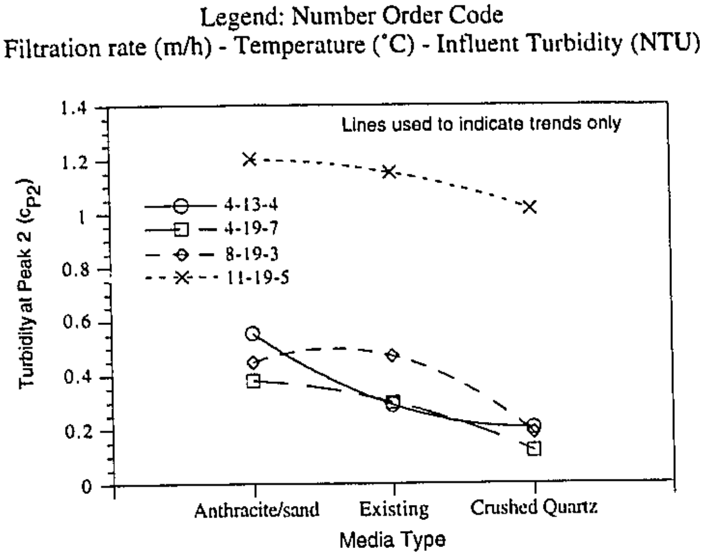

Figure 5.18. Effects of Media Type on Turbidity at Peak 2 for CRF

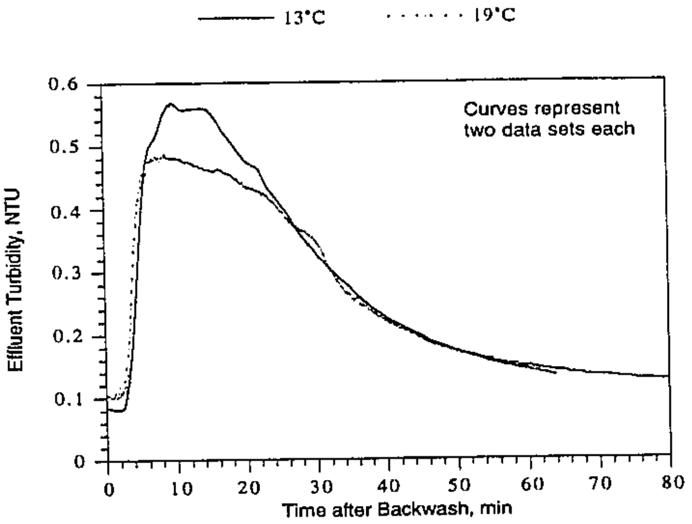

Figure 5.19. Effects of Temperature For anthracite/sand dual-media (Filtration rate = 4 m/h, Influent turbidity = 4 NTU)

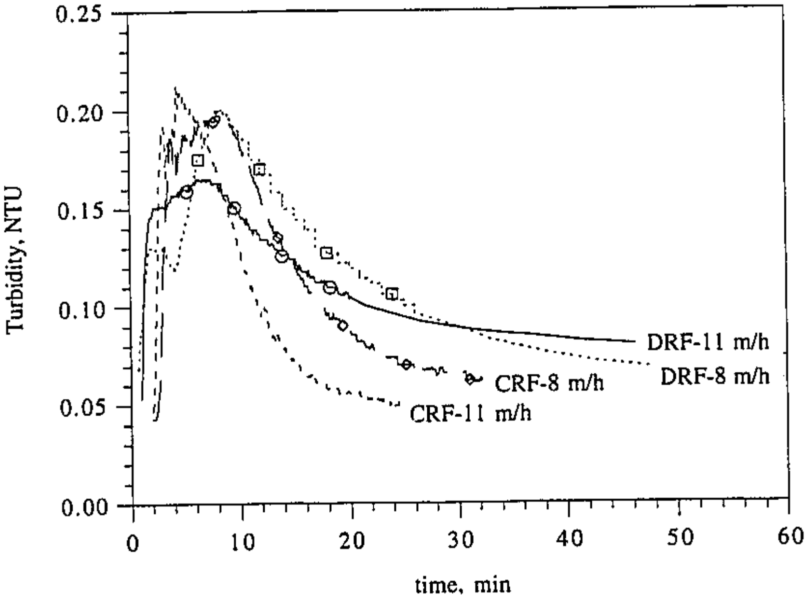

Figure 5.20. Comparison of FRS curves for Constant Rate(CRF) and Declining Rate(DRF) Filter Control Schemes

Chapter 6

General Summary and Conclusions

6.1 General

The research presented in this thesis was primarily based on the study of improvement of water filtration at the Rossdale water treatment plant in Edmonton, Canada, This plant had difficulty in meeting the more stringent standards imposed by the provincial licensing requirement and the very stringent self-imposed in-plant turbidity guidelines. This study was conducted over a three year period. This comprehensive study lead to findings which covered a broad range of plant operating conditions and raw water quality conditions. This approach was considered as an exclusive feature, distinguishing this study from many other pilot and bench scale studies where the results were often site-specific and could not be applied in a general manner to all filtration applications. Careful experimental design and the data collection procedure adopted in this study enabled the development of many general conclusions. Unless otherwise mentioned, findings of this study can be applied for a wide range of situations with careful interpretation.

Chapter 2 of this thesis illustrated the screening experiments conducted with several filter media configurations in constant rate filter control scheme. Although filtration is affected by many variables, at initial stages of this study many variables were kept constant and two media configurations were chosen for further investigations. The key monitoring parameters for screening experiments were: i) the effluent turbidity; ii) turbidity violations of the then proposed stringent standards; and iii) the media performance during sudden filtration rate changes. Characteristics of filtration cycles and monitoring the quality and performance of filtration were discussed in Chapter 2. The effects of filtration rates were also discussed in Chapter 2. Preliminary findings suggested that crushed quartz provided better effluent quality while anthracite/sand dual-media filters gave longer filter runs.

The next phase of this research investigated the effects of polymer addition on the chosen media (Chapter 3). This part of the study also concentrated on physical characteristics of filter media representing abrasion resistance since abrasion can occur during fluidization of media during filter backwash. Abrasion resistance is important for evaluating the durability of the filter media. In addition, the angular nature of crushed quartz, which contains more sharp edges to concentrate charges to enhance particle attraction, may change over time. This in-turn might reduce the filtering ability. Standard test protocols for measuring abrasion resistance were not available. However, some documented test procedures together with scanning electron microscopy (SEM) were successfully used to compare the abrasion resistance of the filter media tested. Filter media's ability to withstand sudden filtration rate changes and recovery to the original state of filtration were also investigated in this part of the study.

Chapter 4 discussed the statistical evaluation of filtration data obtained from a pilot plant study. Due to variations in the influent quality encountered during pilot plant operations, use of simple averages was not adequate to characterize the behavior of filtration over long-term full-scale operations. This chapter provided a detailed discussion of a filtration data transformation procedure that could normally distribute the data. After such transformation, statistical inferences about filter performance could be made and the reliability of filter performance could be assessed.

Initial degradation of product water quality experienced at the beginning of a filter cycle was of concern due to the possible passage of pathogenic microorganisms associated with high turbidity that occurs during that period. Detail evaluation and eventual optimization of factors affecting filter ripening to minimize such unwanted effects were presented in Chapter 5.

Major findings from this study were divided into the following categories.

6.2 Filtration Data Analysis

The use of statistical techniques such as probability plots and frequency histograms was better than using the turbidity profiles alone. Turbidity histograms were also useful for comparison of the average and consistency of turbidity data by visual interpretation. Probability plots were necessary to confirm the compliance to effluent turbidity standards for the recommended percentage of operating time as well as to check the normality of data. Skewness of the effluent turbidity distribution was also a valuable tool for assessing the risk or uncertainty of the change in the average turbidity and for confirming the normality. Filtration data distributions of the effluent turbidity, filter run length and water production capacity were not normally distributed. Therefore, conclusions drawn from simple averages of the above parameters were not appropriate. Due to the non-normality of the observed data, the long-term predictions from the experiments conducted during short periods may not be reliable. Such deviations from normality could be corrected by appropriately transforming the observed data. Different transformations were required for turbidity, FRL and WPC.

6.3 Reliability of Filtration Data

Due to the variation of influent quality in pilot plant experiments, a large number of experiments were conducted. However, the long-term prediction of filter performance required the assessment of reliability of the pilot plant data. Reliability of filtration performance was characterized by a probabilistic model that lead to the estimation of reliability based on the confidence level. Such a reliability model was suggested for the use in the rational design of filtration. Design equations and diagrams were recommended for the estimation of the design value based on the coefficient of reliability. This rational design approach will incorporate the long-term compliance with the regulatory standards, using the results obtained in a brief pilot study or the data obtained from available literature.

Appropriate power transformations were required to normally distribute the observed data. Negative power transformations to the power of -0.4, -0.2, and -0.3 of the observed effluent turbidity, filter run length and water production capacity, respectively, were required to transform the distribution to a normal form from which statistically correct inferences about filtration were made. The standard deviations of the filtration data on the transformed normal scale were homogeneous and 0.25, 0.04 and 0.07 for effluent turbidity, filter run length and water production capacity, respectively. These transformations can be applied under the boundary conditions of this study. Otherwise, short-term pilot tests are preferred to estimate the transformation and design parameters for using the procedure described in this study.

6.4 Durability of Filter Media

During filter backwashing, the filter bed is fluidized and interparticle contact is unavoidable. This leads to abrasion of the filter media and the loss of broken media during the backwash. Tests were used to assess some physical characteristics related to the abrasion resistance of the filter media. Acid solubility of all the media tested in this study were found to satisfy the standards. However, acid solubility of anthracite was more than that of rounded sand and crushed quartz. Scanning electron microscopic photographs of media surfaces generally indicated surface smoothing due to abrasion and deposition. No surface cracks were seen in crushed quartz. However, anthracite contained surface cracks due to abrasion. Particle deposit accumulations on the media surface relate to the lack of particle detachment efficiency during backwash. Long term accumulation of captured particles on the media surface is evident in the existing filter sand which was in service for seven years, approximately. Crushed quartz media surface did not change considerably and no particle accumulation was experienced during the test period. This indicated that efficient particle detachment during backwash can be achieved with crushed quartz. This filter media also had high abrasion resistance and could possibly retain its original shape during long term operations.

6.5 Filter Performance Evaluation

From Phase I of the study, approximately 50 percent improvement of filtrate turbidity and filter run lengths were observed with warm (13°C) water when compared to cold (< 5°C) water. All filter run lengths in this study were limited by the headloss criterion (≤1 m). The filtrate turbidity values showed that the turbidity of all three filter media types investigated in the second phase of the study never violated the 1993 licence requirement for water treatment plants during the operating cycles. However, their individual performances were found to vary at different filtration rates. For crushed quartz and dual-media filters, respective minimum average turbidity, maximum WPC and FRL were achieved at 8 m/h, indicating the possible existence of an optimum filtration rate that compromises between shear detachment and orthokinetic flocculation within the media. Crushed quartz media improved effluent quality more than the other media types tested but anthracite/sand dual-media provided longer FRL and higher WPC. However, the FRL and WPC of the crushed quartz were comparable to that of the existing filter media. For both crushed quartz and anthracite/sand dual-media, the best FRL, WPC and effluent turbidity were obtained at 8 m/h without polymer addition.

Non-ionic polymer addition did not significantly improve the filter performance at the filtration rates tested with the mixing provided in the pilot plant. However, the results may vary with further mixing studies including different polymers. Polymer addition reduced the FRL and WPC at low filtration rates but did not significantly affect the FRL and WPC at higher filtration rates. This may be a result of better mixing (velocity gradient) being provided at high filtration rates resulting in more uniform polymer action. At low velocities, inadequate mixing may have caused localized particle agglomeration and subsequent clogging of filters. Factorial experimental analysis of the data suggested that the polymer addition between 0.02 mg/L and 0.1 mg/L had insignificant effects on the turbidity, FRL and WPC.

Results of the rate change tests suggested that crushed quartz provided substantially better resistance to turbidity increases during rate changes and recovered quicker than the other media types. The filter ripening sequence of crushed quartz was much better than the other media types with very low peak turbidities during ripening.

6.6 Comparison of Various Filter Media

Screening test results indicated that both the crushed quartz media and the dual-media (sand and anthracite) with polymer addition performed better than the existing filter media, meeting the more stringent effluent turbidity standards requirement. The filtrate turbidity values showed that the turbidity of all three filter types investigated in the second phase of the study never violated the 1993 licence requirement for water treatment plants during the operating cycles. However, their individual performances were found to vary at different filtration rates. For crushed quartz and dual-media filters, respective minimum average turbidity, maximum WPC and FRL were achieved at 8 m/h filtration rate.

Histograms and the variation of the average turbidity suggested that the crushed quartz filter media exhibited the most consistent operation. For all three types tested, the consistency was reduced at 12.5 m/h filtration rate. Comparison of filter media based on factorial experimental design principles suggested that the average turbidity of crushed quartz was the best (lowest value of the three media tested) but its WPC and the filter run length were the lowest. The dual-media outperformed the other two types with respect to WPC and FRL which are similar for crushed quartz and the existing media. Crushed quartz was the most abrasion and shock resistant filter media among those tested.

6.7 Optimization of Filter Ripening Sequence

The ripening curve was characterized by the turbidities and the time to reach the peaks and the end of the filter ripening for the purpose of analysis and optimization. The cumulative solids released to the effluent during the filter ripening period was also important in defining the filter ripening characteristics. This incorporates the total amount of particles released during ripening in concern with the immature state of the filter bed. The end of the filter ripening can be defined as the instant where a significant change in the effluent turbidity reduction rate occurs, beyond which the rate becomes similar to normal filtration values. The influent solid flux rate to the filter, which is the product of filtration rate and influent concentration, was also a key factor in the filter ripening in addition to the filtration rate, influent turbidity, media type and temperature.

Conclusions about the influence of operating parameters on the filter ripening characteristics can be drawn. Filtration rate generally governed the time related characteristics of the ripening curve, while the influent solid flux rate influenced the turbidity parameter more than the influent turbidity. Warm waters produced better ripening conditions compared to cold water. Quicker ripening, lower FRS flux and higher peak turbidities were observed in CRF when compared to DRF. Crushed quartz also produced the lowest peak turbidities among the media studied. In view of quality and the risk of microbial contamination, crushed quartz would be a better choice than the other media types tested.

Depending on the number of filter units and the plant production capacity, water treatment plant operators may be interested in minimizing the duration of FRS and/or the water wasted during filter-to-waste procedure. Based on this study, optimization of some filter operating parameters was possible. Water wasted during filter ripening can be minimized by selecting a suitable filtration rate for the 'slow-start'. For constant and declining rate filter operations, a starting filtration rate of 8 m/h was the optimum for reducing the filter ripening sequence as well as to minimize the water wasted during filter-to-waste procedure. This can be used in conjunction with filter-to-waste procedure and coagulant addition to backwash. Once the filter ripening is over, the filtration rate can be slowly adjusted to the operating rates. The existence of the optimum filtration rate depends on the particle transport and shear detachment aspects, whichever dominates at a given filtration rate. Though optimum influent turbidity could not be established directly from the results, by optimizing the influent solid flux rate, optimum influent turbidity was found to be between 2.5 to 4.4 NTU. This can be achieved by controlling the pretreatment processes and/or by coagulant addition to the filter influent.

6.8 Media Selection for the Rossdale Water Treatment Plant

All filter media types tested produced filtered water that complied with the current turbidity standards (< 1 NTU). Average effluent turbidities of the crushed quartz media were the lowest among those tested under all experimental conditions. This was also supported by the results of factorial experimental analysis. Reduced capture efficiency of the anthracite portion may have caused higher average turbidities for the anthracite/sand dual-media than for the crushed quartz.

The dual-media produced more water during a filter cycle. However, its use in the existing filters at Rossdale water treatment plant was restricted by inadequate full scale filter depth which could not be modified to accommodate the anthracite expansion during backwash. In view of effluent turbidity, dual-media filter quality was borderline to the plant operating criterion at Rossdale water treatment plant (< 0.1 NTU) while crushed quartz provided turbidities well below the criterion. By using the reliability-based design procedure which is given later in this chapter, design turbidity must be less than 0.07 NTU for satisfying the effluent turbidity requirement of 0.1 NTU (in-plant guideline at the Rossdale water treatment plant) for 95 percent of the operating time. Such stringent turbidity can be achieved only by the crushed quartz at the plant operating conditions at the Rossdale water treatment plant. Though the FRL of the crushed quartz was 40 to 60% lower than the dual-media, it was comparable to that of the existing mono-media. Crushed quartz also exhibited better filter ripening characteristics.

Considering the facts that: (i) the goal was effluent quality improvement to <0.1 NTU; (ii) inefficiency of polymer addition at low filtration rates; (iii) abrasion resistance; (iv) resistance to sudden flow rate changes and; (v) filter ripening sequence, crushed quartz mono-media without any polymer addition may be the best alternative under the prevailing physical and operational conditions among those media tested in this study. This would improve the effluent turbidity to meet the stringent quality goals at normal filtration rates under the existing physical conditions of the filters. This is especially true when considering the normal operating filtration rate is in the range of 8 m/h.

Declining rate filtration is expected to give better performance than constant rate filtration (Cleasby and DiBernardo, 1980). Therefore, switching the filters to a declining rate control scheme would provide better effluent quality. Considering the above factor in conjunction with the findings of this study, filters at the Rossdale water treatment plant were refurbished to contain crushed quartz as filter media and converted to declining rate filtration. Initial operating results conducted in both constant rate and declining rate filter control schemes indicated that the filters now meet and better the 0.1 NTU filtrate turbidity requirement (in-plant guideline). Longer filter runs (60-hour filter cycles) and excellent filter ripening characteristics are experienced after refurbishment.

6.9 Limitations of Study

This study was conducted in extreme climatic conditions prevailed during Fall 1991 to Spring 1994 in the treatment plant location and hence it was able to cover a wide range of plant operating conditions. Since the study was conducted over a long period, the results obtained from this study will be valid for a wide range of parameters encountered in this study. Inferences about the filter media types can be extended to other filter media which exhibit similar physical characteristics. The filter influent in this study was alum-coagulated, lime-softened and clarified raw water from the North Saskatchewan River. The water temperature varied from 3°C to 20°C. The results presented in this study were limited to the boundary conditions of this study. Care should be exercised in application of the results of this study for situations where the operating conditions differ widely, unless otherwise specified.

6.10 Summary of Reliability-based Filtration Design

The turbidity regulations suggest that the average effluent turbidity of combined filters is not to exceed the standard (X_s) for a specified percentage of time. The percentage compliance time can be considered as the reliability and the significance level α, which is defined as 1-.01•[percentage compliance], is chosen accordingly. Then the design effluent turbidity can be determined either by:

(i) Using Equation 4.19 with appropriate values of λ and σ' (Table 4.7) and $Z_{(1-\alpha)}$ (Table 4.8);

or

(ii) using Figure 4.9 which graphically illustrates the design effluent turbidity.

6.11 Conclusions

Major conclusions from this study can be divided into different aspects of improving water filtration as mentioned below.

6.11.1 Statistical Inferences

Conclusions involving the statistical evaluation of filtration data included:

1. Due to the non-normality of the observed filtration data such as effluent turbidity, filter run length and water production capacity, negative power transformations (-0.4, -0.2, and -0.3, respectively) were required to normally distribute the data from which statistical inferences could be made.

2. That fact that the "t-test" which is considered robust to non-normality was not true in filtration data due to severe non-normality. Therefore, the "t-test" of the filtration data was performed on the normally distributed data after transformation.

Conclusions involving the reliability based design procedure to evaluate pilot plant results in view of the water quality standards included:

1. The design procedure presented in section 6.10 can be used to select the design parameter when standards or requirements are predetermined.

2. This design approach can be used to establish a practical value of percentage compliance of effluent turbidity, in terms of achievability in treatment plants.

6.11.2 Improvement of Filter Performance

Conclusions involving the optimization of filter ripening sequence included:

1. The filter ripening sequence was also characterized by the ripening flux, which represented the amount of solid material released to the effluent before the filter bed matures. This was in addition to time and turbidity characteristics,

2. The end of the filter ripening was defined as the instant where a significant change in the effluent turbidity reduction rate occurred, beyond which such rate became similar to normal filtration values.

3. The influent solid flux rate to the filter, which was the product of filtration rate and influent solids (or turbidity) concentration, was also a key factor in the filter ripening in addition to the filtration rate, influent turbidity, media type and temperature. It also governed the filter ripening sequence more than the influent turbidity.

4. Filtration rate generally governed the time related characteristics of the ripening curve, while the influent solid flux rate influenced the turbidity parameters more than the influent turbidity. Warm waters produced better ripening conditions compared to cold water.

5. Quicker ripening, lower FRS flux and higher peak turbidities were observed in CRF when compared to DRF. Crushed quartz also produced the lowest peak turbidities among the media studied.

6. There exists an optimum filtration rate which minimized the quantity of water wasted during 'slow-start' and filter-to-waste procedures. By starting filters at a filtration rate of 8 m/h and by maintaining an influent solid flux rate of 20 to 35 NTU•m^3/(m^2•h), filter ripening sequence can be well reduced to provide better quality water.

Conclusions involving physical characteristics of filter media included:

1. Acid solubility of anthracite was higher than that of crushed quartz and the existing media. Surface cracks of anthracite were evident in scanning electron microscopic photographs.

2. Particle detachment from the crushed quartz during filter backwashing was excellent. Little or no accumulation of deposits was seen during the study period compared to the other media types tested. Crushed quartz also had the best abrasion resistance among the three media types tested.

Conclusions involving operational characteristics of filter media included:

1. Crushed quartz provided the lowest and most consistent effluent turbidity among the media types tested for the operating conditions prevailed in this study (no polymer was added).

2. Anthracite/sand dual-media filters provided the longest filter runs and highest water production by taking advantage of the coarser anthracite media portion which had a higher porosity.

3. Crushed quartz provided the best resistance to hydraulic surges in the influent. It also exhibited the quickest recovery to original filtration state.

4. In view of quality and the risk of microbial contamination during filter ripening, crushed quartz was a better choice than the other media types tested.

Conclusions involving operational characteristics of filtration included:

1. At 8 m/h filtration rate, optimum operating conditions were observed for crushed quartz media which was a result of a compromise between shear detachment and orthokinetic flocculation within the media.

6.12 Recommendations for Further Study

1) Since a comprehensive database of pilot plant filtration data is available for crushed quartz and the fact that crushed quartz is now used in a full scale plant, it will be very useful to investigate the scale-up factors and the validity of pilot plant data for full scale filtration applications.

2) Existing mathematical models do not correctly predict full scale filtration performance (Ives, 1966; Davis, 1983). This is partly because they were established from laboratory scale filtration units which do not properly represent the real water situations and due to some of the sampling procedure. By indirectly measuring the filter bed saturation by the headloss, mathematical models can be formulated using pilot plant data which possibly predict the full scale filter performance. However, this would require pilot plant operation under a wide range of influent and operating conditions.

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