Granular Media Filtration for Water Treatment Applications

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The intent of this paper is to provide cursory information about filter design and function. This knowledge will provide a basis for understanding the needs of the customer wishing to monitor the filtration process. There is no attempt to provide an exhaustive description of various filtration configurations or a comparison of relative merits of the various filter designs, troubleshooting or operational theories. Consult citations in the list of references if more detailed information is desired.

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Brief History of Water Treatment

References to water treatment including filtration and its importance to the health and welfare of man trace back 4000 thousand years: “It is good to keep water in copper vessels, to expose it to sunlight and filter through charcoal.” And, “…heat foul water by boiling and exposing to sunlight and by dipping seven times into it a piece of hot copper, then to filter and cool in an earthen vessel. (Ref 8, pg 1).

In these words you see disinfection, coagulation, sedimentation, and filtration – the same four basic steps - a multiple barrier approach - used in water treatment today. The science has progressed over the last 4000 years with variations and improvement on techniques described long before the science was sufficient to explain the reason the treatments were necessary or how they worked. Little has changed in water treatment except our understanding of the science and our ability to measure.

Progress of Filtration - Ancient Times to 1800

Date	Event
2000 BC	Early Sanskrit writings: 1. "It is good to keep water in copper vessels, to expose it to sunlight, and filter through charcoal. 2. "Impure water should be purified by being boiled over fire…or it may be purified by filtration through sand and coarse gravel."
1500BC	Wick siphons used by Egyptians
	Biblical references to water treatment in Exodus (15:22-27; 17:1-7)
1000 BC	Biblical reference to water treatment in Kings (2:19-22)
500 BC	
	1. Hippocrates suggests rain waters should be boiled and strained. He suggested a cloth bag - later became known as the Hippocratic sleeve. 2. Filtration through porous vessels common knowledge among the Greeks
	Infiltration galleries described in Alexandria, Egypt
	Egyptians filter water through earthen vessels
500 AD	Filter Cisterns used in Venice, Italy.
	Greek physician, Paulus Aegineta suggests, "marshy, saltish or bitumunous waters…were benefited by straining."
	A Persian physician advises travelers to strain water through cloth
1000 AD	
1500 AD	1. Household sand filters used in France. 2. Sir Francis Bacon suggests clarification and filtration of water may, "improve health and increase the pleasure of the eye."
	1. 1685: First known illustrated description of sand filters published by Luc Antonia Porzio. 2. Mid 1700's Numerous descriptions of filtration with cloth and sand for household, municipal and industrial use in England, France and Japan. 3. First known patent granted for a filtergranted to Joseph Amy in France in 1749. The filter involved an earthen, lead or pewter vessel and media of sponges or sand.
1800 AD	

Figure 1: Progress of Filtration Ancient Time to 1800 (Ref 8)

Importance of Measurement in Water Treatment

As paraphrased from Scottish mathematician and physicist Lord Kelvin - William Thomson Kelvin, 1824-1907: ***If we can measure that of which we speak and express it in number, we know something of our subject. If we cannot measure and express it as a number our knowledge is meager and unsatisfactory.***

The sentiment expressed by Kelvin is what has provided a market for Hach Company's products. Process control and quality improvement - whether in manufacture of analytical instruments, treatment of potable or industrial waters and wastewaters, manufacture of rockets and widgets – depend on accurate, reliable measurement. At Hach, maintaining and improving the quality of the product requires identifying and eliminating variation in the manufacturing process. So too with water treatment - variations in the process must be identified and eliminated to maintain and improve the treatment process.

When Hach Company introduced the first practical on-line turbidimeter, CR Low Range Turbidimeter (the 'CR' stood for 'continuous reading'), in about 1957 it provided water treatment operators a means to continuously monitor the filtration process thus to observe variation in the process; then, to reduce variation in the process and thus to improve quality. That instrument's basic optical configuration is still employed today in our 1720E Low Range Turbidimeter as well as the FilterTrak 660 Laser Nephelometer. It is not a coincidence that as the sensitivity and accuracy of laboratory and on-line process turbidimeters have improved the quality of the drinking water has improved and the regulatory requirements have become more stringent. Herbert Hudson (Ref. 26, pp 5-6) in 1981 observed:

> More than to any other development, credit for improvement of water quality is due to the development of reliable water quality monitoring devices in the last two decades. These include instruments that measure and record pH, residual chlorine and turbidity. A variety of other quality-sensing devices is available, but the three foregoing are the most commonly used. These devices enable the operator to identify episodes of deficient treatment which in the past frequently went unnoticed. Now these deviations in quality are conspicuously apparent on the quality-sensing recorders and corrective action can be taken promptly.
>
> In a number of plants, filtered-water turbidity levels prior to the initiation of turbidity monitoring were commonly held in the range of 0.2-0.5 NTU. After the initiation of monitoring, operators could observe episodes of quality deterioration and develop techniques to prevent such episodes, gradually revising their personal quality goals to new levels and commonly reducing the filtered-water turbidity to 0.02-0.05 NTU, an order of magnitude improvement. This process takes one to two years but once having become accustomed to the production of water quality at such levels, the operators of these plants become intolerant of filtered water with more than about 0.06 NTU.
>
> One of the axioms of water quality control is that, as the clarity of water is improved by improved treatment, there is a parallel reduction of color, taste and odor, bacteria and viruses, and often of iron, manganese and alumina levels…

Hudson hits the nail squarely on the head with one slight correction. In the 1950's and early 1960's turbidity was commonly measured with the Jackson Candle Turbidimeter. About the best one can truly discriminate with the Jackson Candle unit is about 25 NTU! The advent of the Hach on-line turbidimeter in the mid 1950's and the Model 1860 laboratory turbidimeter in about 1964 provided tools for operators to measure reliably down to and below 1 NTU. With a nearly continuous effort, Hach Company's turbidimeters (nephelometers) now provide reliable measure to 0.05 NTU and below.

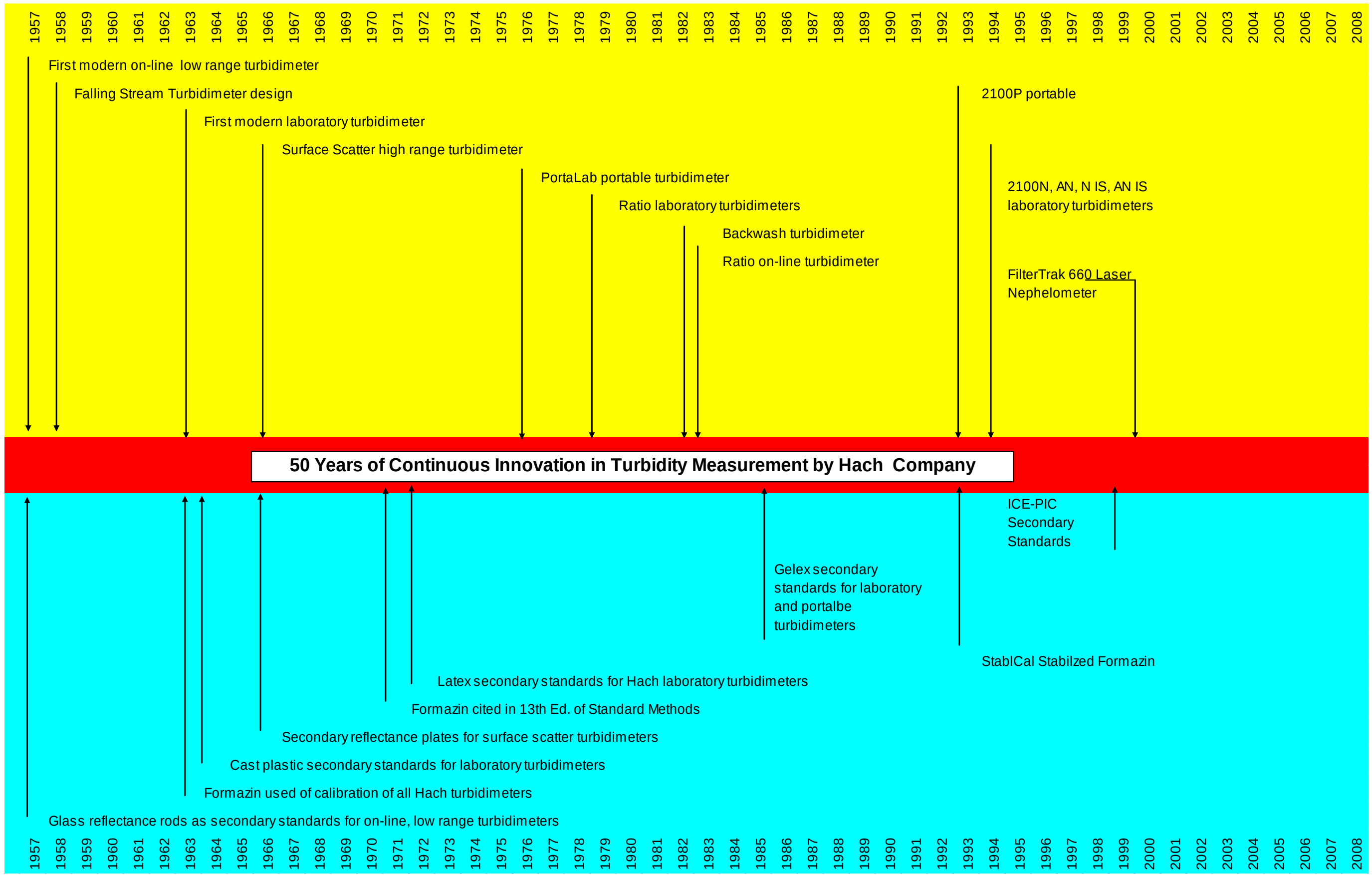

Figure 2: Hach Innovation in Laboratory and Process Turbidimeters and Standards

In the 1960's 5 NTU was commonly acceptable for finished drinking water turbidity. By the mid 1970's and the enactment of the Safe Drinking Water Act the standard for turbidity was lowered to 1 NTU. By the mid 1980s the standard became 0.5 NTU, now 0.3 NTU. As Hudson points out, now the expectation is to be consistently below 0.1 NTU and many facilities consistently below 0.05 NTU. Initially Hach Company provided the means of measurement and thus impetus to improvement. By the mid 1990's increasing use of membranes and demands of the customer drove us to the FilterTrak 660 for more sensitivity and more repeatable and precise measurements below 0.05 NTU. So, improvement has not been, as Hudson suggests, a decade but rather in excess of two decades! Remarkable!

Water Treatment, Filtration and Public Health

Many diseases that can be contracted by humans can be waterborne – cholera, typhoid, amoebiasis (amoebic dysentery), giardiasis, polio, legionnaires disease, paratyphoid, salmonella, shigellosis are but a few. Bacteria, viruses, protozoans, helminthes all can be and are waterborne and can cause illness in humans. Water is not the primary mode of transmission of any disease but when water carries an agent capable of causing infection it is a medium that can carry the infection over a wider area to a more diverse population in a shorter period of time than almost any other mode of transmission except perhaps air. Water also is important in overall sanitation as it is used to keep clean other objects and surfaces with which humans come in contact.

> As is the case with other filth diseases, paratyphoid fever is communicated by man's transfer of infected dejecta to his mouth either directly or by means of a vehicle such as food or water…The short distance between man's contaminated fingers and his mouth lends force to the importance of proper and safe disposal of infected fecal matter and of personal cleanliness as a means of severing the lines of communication of this disease. (Ref 32, pp 20-21)

Up to the mid 1800's the importance of water to transmission (or prevention of transmission) of disease was not fully appreciated despite a previous 3000 years of treatment efforts for water. Filter cisterns were used in Venice, Italy around 500 A.D that were very similar in construction to the slow sand filter invented in Scotland in the 1800's. Early water treatment efforts were, as Sir Francis Bacon indicated in the early 1600's to "…increase the pleasure of the eye." By the early 1800's filtration was not uncommon – in 1804 Paisley, Scotland became the first city to receive filtered water for an entire city. Glasgow, Scotland in about 1806 became the first city to pipe treated water to each residence rather than delivered in individual vessels or on carts. It was John Snow's work in the Cholera outbreak in London in the 1850's that established a firm link to water and transmission of disease. It would be another 25 years or so in the 1870's before the work of Pasteur, Koch and others led to the germ theory of disease.

Figure 3: Children are shown gathering water from a central water post

The water provided at this post (Ref 41, Jasia, Rohtak District, India today) is settled, filtered and disinfected, potable water. Many rural and even urban areas in some parts of the world still lack an adequate supply of safe water.

A cholera outbreak in the area of Hamburg Germany in 1892 made the importance of treatment very vivid: (Ref 37, 1893, p 643)

> The experiences of Hamburg, Altona and Wandsbeck (*sic*, Wandsbek) are exceedingly instructive. These three cities which are adjacent to each other form practically one city excepting their water supplies are separate. Wandsbeck is supplied with filtered water from a lake not exposed to contaminating conditions; Hamburg gets its water from the river Elbe above the city, it used the water in an unfiltered condition; and Altona is supplied with filtered water taken from the river below the city. The points to be observed are that while Hamburg was frightfully stricken with cholera, Altona and Wandsbeck were practically free from it. It is of further interest to consider that Hamburg took its water from a point in the river where contamination was slight while Altona drew its supply from the river after it received the sewage of 800,000 people. The line of demarcation was very striking. On one street which for a long distance forms a boundary, the Hamburg side was badly infected…while the Altona side remained free from it. Koch *[Robert Koch, advanced 'Koch's Postulates' stating the criteria for establishing a relationship between a microorganism and disease]* attributes the comparative freedom of Altona to the filtration of its water…The experiences of the present year, however, have shown that a filter bed of itself is not sufficient protection. The bed must be complete in every particular and the filtration must be conducted in the most thorough and painstaking manner with the frequent bacteriological examinations for the control of the filter. Epidemics of typhoid fever in Altona have demonstrated the existence of a connection between the disease and imperfect filtration.

Figure 4: Modern day Hamburg, Germany. (Google Maps)

The impact of current water treatment practices on public health can be seen in the following illustration:

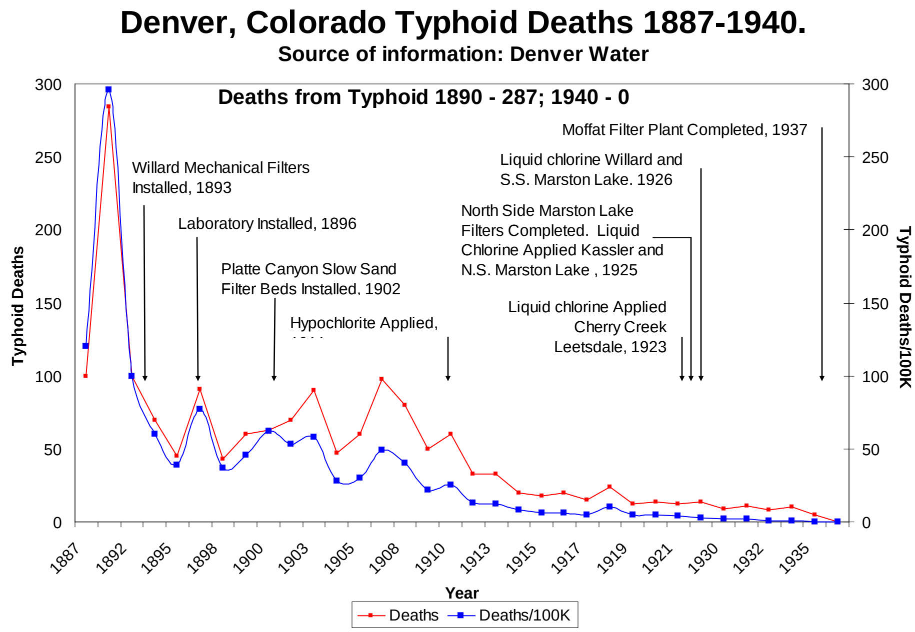

Figure 5: Denver, Colorado Typhoid Deaths

Importance of the Multiple Barrier Approach

Many water treatment practices date back hundreds and in some cases thousands of years. But today:

- Understanding of the science of treatment is better
- Modern measurement tools are better
- There is a better appreciation for the multiple barrier approach to water treatment
- Individuals using the tools and operating the processes are better educated and trained

Sedimentation, filtration, disinfection or measurement individually is not sufficient to provide the needed level of safety. As illustrated in the data from Denver Water, solving the problem of typhoid involved sedimentation, filtration, disinfection and measurement.

Recalling Hudson's comment from 1981 - "More than to any other development, credit for improvement of water quality is due to the development of reliable water quality monitoring devices in the last two decades." The key to process control is finding and then correcting process variation. It is not enough to just treat the water, one must measure or the knowledge is "meager and unsatisfactory."

While the beginnings of filtration can be traced back to citations from 4000 B.C., progress accelerated from the early 1800's to the early 1900's. In relatively rapid succession:

- Invention of slow sand filtration in Scotland
- Installation of a city-wide means of distributing filtered water in Glasgow, Scotland
- Establishment by John Snow of a firm link to water in the spread of Cholera
- Work by Louis Pasteur and Robert Koch leading to the Germ Theory of Disease

- Development of rapid filtration in the United States*
  *Referring to a treatment plant in Dhaka, India (now Bangladesh) in the 1870's, Mau (Ref 30) indicated, "Dhaka had one of the most modern and rapid sand filtration systems for surface water in the 1870's. This plant was almost a duplicate of the plant that was built several years later in Louisville, Kentucky, and before a similar system was patented in the United States."

Some authors have suggested that the United States came to adoption of filtration somewhat late as it did not become common until after the Civil War. By the mid-1800's filtration by various means was being carried out in many cities in Europe. It may be the timing of use of filtration in the United States was more a matter of necessity than 'being late.' By the early 1800's population densities in Europe and the concomitant larger volumes of waste were already a problem. The Civil War and post Civil War eras in the United States corresponded to population growth, greater mobility of the population, increased industrialization and increased municipal and industrial waste.

It is perhaps fitting to conclude this discussion with a portion of a letter from 1893 by George W. Fuller, Lawrence, Massachusetts (namesake of the prestigious Fuller Award from the American Waterworks Association. It is worth noting three Hach Company employees have received the Fuller Award: Clifford and Kathryn Hach and Danny Hutcherson). The importance not only of treatment but of measurement is cited by Fuller when he observed: (Ref 18, 1893, p 686.)

> During the past 40 years many filter plants have been constructed in Europe and numerous experiments in the filtration of water have been made particularly during the past decade. This is largely due to bacteriology which enables us to determine the actual efficiency of filters with regard to the removal of bacteria…
>
> In summing up our present knowledge upon the removal of pathogenic bacteria from drinking water, we may state that in addition to the experience of certain European cities, the Lawrence investigation, covering a period of more than five years and including the bacterial examination of more than eleven thousand samples of water, indicate that it is entirely practicable to construct filters that will economically purify and remove more than ninety-nine percent of bacteria which may be present in the unfiltered water.

Fuller's observation is interesting but it must be noted that ninety-nine percent removal (2-log) of bacteria will not meet today's standard. It is important to always keep in mind the importance of the multiple barrier approach. Filtration alone is not sufficient; it must be followed by disinfection.

The Filter – A Complex Piece of Equipment

Treatment plant operation personnel typically do not consider a granular media filter as a piece of equipment. Filtration is viewed as a distinct unit process and filtration is accomplished with a filter but somehow the connection that a filter is actually a piece of equipment never occurs to many operators or managers. In reality the granular media filter is easily the most costly and most complex piece of equipment in a water filter plant. And, as was seen earlier, careful and correct operation of this piece of equipment is absolutely essential to public health. Returning again to the experience in Altona, Wandsbeck and Hamburg Germany in 1892:

> The experiences of the present year, however, have shown that a filter bed of itself is not sufficient protection. The bed must be complete in every particular and the filtration must be conducted in the most thorough and painstaking manner with the frequent bacteriological examinations for the control of the filter.

Operation of this complex tool is often left to monitoring from a control room as utilities try to minimize operational cost and thus operations personnel. This makes the role of instrumental monitoring of all aspects of the filtration process even more important.

Filter Media and Media Specifications

Specifications for filter media generally follow the AWWA Standard for Granular Filter Material, ANSI/AWWA B100-01, American Waterworks Association (Ref 7, page xi):

> In general, for a given pretreatment of raw water and at a given filtration rate, coarse media will permit longer filter runs between washings than fine media. With good pretreatment facilities and close technical control, coarse media will yield water of satisfactory quality. With all other conditions fixed, removal of particulate matter is a function of both media size and filter bed depth, and removal generally improves with greater filter depth or with smaller media size, or both.

In addition to silica sand, filter materials may be chosen from one or more of the following materials.

Anthracite coal may be used alone in a deep bed mono-media; in dual media filters in combination with sand; and, also in multimedia filters where anthracite, sand and a high density material such as garnet are used. Anthracite typically functions as a top coarse layer in dual or multimedia beds to provide storage volume for a large amount of solids (thus providing long filter runs) while the under laying sand media provides a finer filter media to stop solids passing all the way through the anthracite.

> The coarse-to-fine grading tends to combine the longer filter runs characteristic of coarse media, with the superior filtration characteristic of fine media for improved overall performance. Proper selections of particle size range and specific gravity for the different layers of media are necessary to maintain the coarse-to-fine gradation during filtration and after repeated backwashing. (Ref 7, pg xi)

Granular activated carbon (GAC AWWA Standard B604-05) may be used alone (mono-media) or in combination with sand. GAC provides much the same benefit as using anthracite coal with the additional benefit of adsorbing materials that cause taste and odor and other organics that may contribute to formation of trihalomethanes, THMs. The need to periodically 'reactivate (regenerate)' or replace the GAC to maintain the absorption capability is a significant consideration when considering use of GAC in this way. GAC not only requires regeneration – alone a significant expense – but during filtration, backwashing and removal for regeneration the media will become damaged so it must be regraded for uniformity coefficient and effective size. This process may require 10% or more of the media to be replaced with new media. The uniformity coefficient and effective size specification varies depending on the source of the GAC – bituminous coal, lignite coal or wood. But for an approximate 10x20 mesh size, the uniformity coefficient is ≤ ~1.6 and effective size is ~ 0.7-1.1. See AWWA B604-05 pg xiii for a table of values for the three sources and also a range of mesh sizes.

High density materials are used in multimedia filters. Multimedia filters typically have an upper layer of anthracite coal, a middle layer of silica sand and then a lower layer of high specific gravity (high density) material. This is meant to allow higher filtration rates which might carry solids deep into the sand layer as well as the anthracite. The high density material then provides a 'back stop' to the sand in a similar way the sand provides a back stop for the anthracite. 'Garnet' is the rather generic description used for the high density material. A family of aluminum silicate minerals may be referred to as garnet. For example: Almandine: $Fe_3Al_2(SiO_4)_3$; Pyrope: $Mg_3Al_2(SiO_4)_3$ and Spessartine: $Mn_3Al_2(SiO_4)_3$. Some high iron content minerals may be used.

Selection of filter materials to be used either alone or in combination with other materials require careful attention to certain physical and chemical characteristics including uniformity coefficient, effective size, specific gravity (density) and acid solubility. The table below summarizes the general requirements of common filter materials (Ref 7, pp 3-5)

Filter Material	Uniformity Coefficient	Effective Size	Specific Gravity	Acid Solubility
Silica Sand	< 1.7	0.35 to 0.65 mm	> 2.5	<5%
Anthracite	< 1.7	0.6 to 1.6 mm	> 1.4	<5%
High-Density	< 2.2	0.18 to 0.60 mm	> 3.8	<5%

Figure 6: Filter Media Specifications

Where: (Ref 7, pp 2-3)

Uniformity Coefficient: A ratio calculated as the size opening that will just pass 60 percent (by dry weight) of a representative sample of the filter material divided by the size opening that will just pass 10 percent (by dry weight) of the same sample.

Effective Size: The size opening that will just pass 10 percent (by dry weight) of a representative sample of the filter material; that is, if the size distribution of the particle is such that 10 percent (by dry weight) of a sample is finer than 0.45 mm, the filter material has an effective size of 0.45 mm.

Media Support and Underdrain Systems

The filter media overlays a drain system meant to uniformly collect filtered water (filter effluent). A variety of underdrain systems have been used. One of the simplest and earliest systems is a simple array of perforated pipes – pipe laterals - uniformly placed under the media. It is unlikely one will encounter pipe laterals in new construction today but it may be encountered in filter rehabilitation projects for treatment plants built in the early to mid 1900's.

Depending on which underdrain system is used, there may be a need for additional support media to prevent the filter media from migrating into the underdrain system. For example with a pipe lateral system there may have been a system of graded gravel under the filter sand. The fine sand would have been underlain with successive layers of coarse sand then various sizes of gravel finally ending with stones 2-3 inches in diameter. In other systems the underdrain system has pores small enough that no support media (gravel) is necessary. Regardless of design the underdrain system:

- Must support the media,
- Uniformly collect filter effluent and

- Uniformly distribute backwash water to the filter in such a manner as to not disrupt the media.

A design occasionally used is the Wheeler Bottom. The Wheeler bottom is essentially series of inverted pyramids. Each pyramid then is fitted with a series of ceramic spheres placed in the pyramid. A layer of graded gravel is placed on top of the ceramic balls to support the filtration media above and also to distribute backwash water.

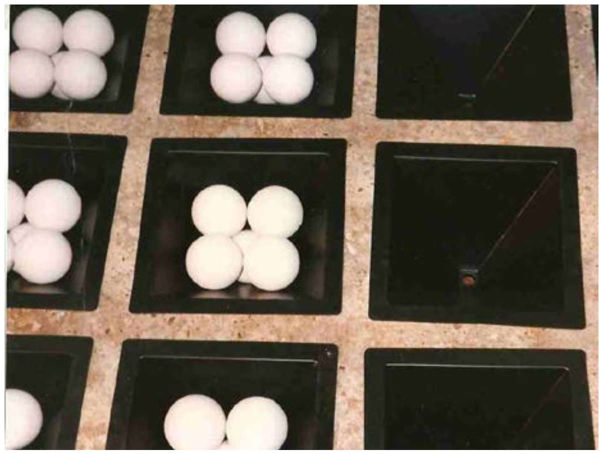

Figure 7: The Wheeler Filter Bottom

A Wheeler Filter Bottom during installation. Photo courtesy of Chris Harris, Chief Operator, City of Batesville Water Works, Batesville, Arkansas.

Figure 8: Wheeler Bottom Variations

Left photo - Wheeler Filter Bottom. Roberts Water Technologies manufactures a porous plate bottom to retrofit the Wheeler Bottom without having to remove the pyramidal structures (middle and right photos). The ceramic balls are removed and the porous plate simply clipped in place. Replacing the balls with the porous plate eliminates the need for support gravel. Removing the support gravel allows more filter media to be installed or increases the free board or both during filter rehabilitation projects.

Other designs included ceramic, plastic and fiberglass blocks, and flat plates fitted with nozzles of various designs.

Figure 9: Leopold Type-S Underdrain
Made from high density polyethylene, this type of underdrain is widely used and designed specifically for air scour as well as a water backwash. This block is fitted with the Leopold IMS cap (integral media support – a porous plate of a synthetic material) eliminating support media. A similar block and porous plate cap also are manufactured by Roberts Water Technologies, Inc.

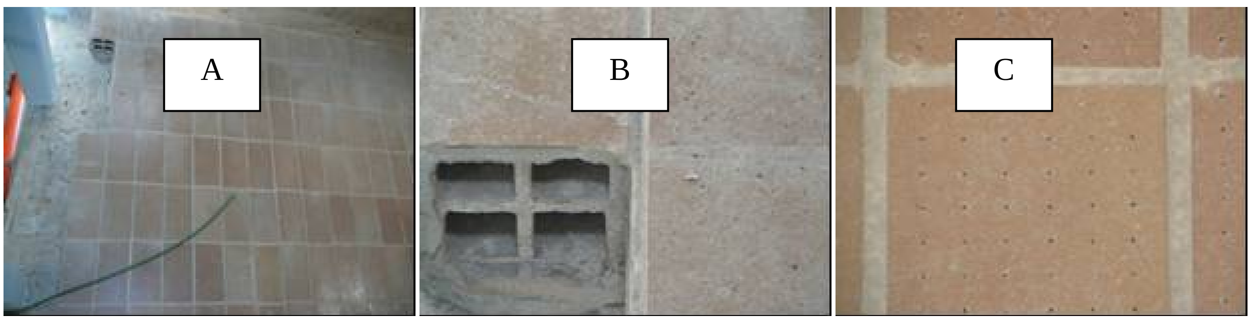

Figure 10: Leopold Ceramic Block Dual Lateral Underdrain.

This underdrain is very common though no longer in production. A complete filter bottom (underdrain) is shown at left (A). In (B) one can see the dual lateral. Backwash water entered the lower laterals. Holes about one inch in diameter permitted water to flow from the lower laterals to the upper laterals. Small orifices (C) in the upper laterals distributed the water uniformly to the filter media. During filtration the small orifices collected filter effluent uniformly. This type of underdrain required use of support gravel between the media and the underdrain. Today the Leopold Type-S or other underdrain would replace this design. These photos were taken during removal of the ceramic block underdrain system. It was replaced with the Leopold Type-S blocks.

Overview of Granular Media Filtration Technologies

A large number of filtration designs have been developed and are in use – slow sand, rapid sand, dual media, deep bed dual media, deep bed mono media, multimedia, upflow, down flow, bi-flow, cross flow, etc. During the course of making visits to water plants one will likely encounter variations not described here. Slow sand, rapid sand, and multimedia however are by far the most common. In recent years deep bed designs using dual media or mono-media are gaining popularity in new construction and filter rehabilitation projects.

Typical Conventional Filtration Media Specifications								
Filter Type	Slow Sand		Rapid Sand		Dual Media (anthracite)		Multimedia (anthracite)	
	Metric	English	Metric	English	Metric	English	Metric	English
Filter Media Depth	1 m	3.23 ft.	0.66 m	2 ft.	0.5 m	1.6 ft	0.5 m	1.6 ft
Water Depth	1 m	3.23 ft.	2-3 m	6-9 ft	2-3 m	6-9 ft	2-3 m	6-9 ft
Filtration Rate	0.12 m/hr.	0.05 gal/ft^2/min	4.89 m/hr	2 gal/ft^2/min	12.22 m/hr	5 gal/ft^2/min	17 to 24.5 m/hr	7 to 10 gal/ft^2/min
Effective Size	0.2-0.35 mm		0.35-0.65 mm		0.35-0.65 mm (sand); 0.6-1.6 mm (anthracite)		0.18-0.60 (Garnet); 0.35-0.65 mm (sand); 0.6-1.6 mm (anthracite)	
Specific Gravity	>2.5 (sand)		>2.5 (sand)		>2.5 (sand); >1.4 (anthracite)		>3.8 (garnet); >2.5 (sand);>1.4 (anthracite)	
Solids Penetration	13 mm	0.04 ft.	75 mm	0.25 ft	450 mm	>1.5 ft	>500mm	>1.5 ft
Storage Capacity	0.005 m^3/m^2	0.014 ft^3/ft^2	0.04 m^3/m^2	0.12ft^3/ft^2	0.22 m^3/m^2	0.66 ft^3/ft^2	>0.22 m^3/m^2	>0.66 ft^3/ft^2

Figure 11: Conventional Filter Media Specifications

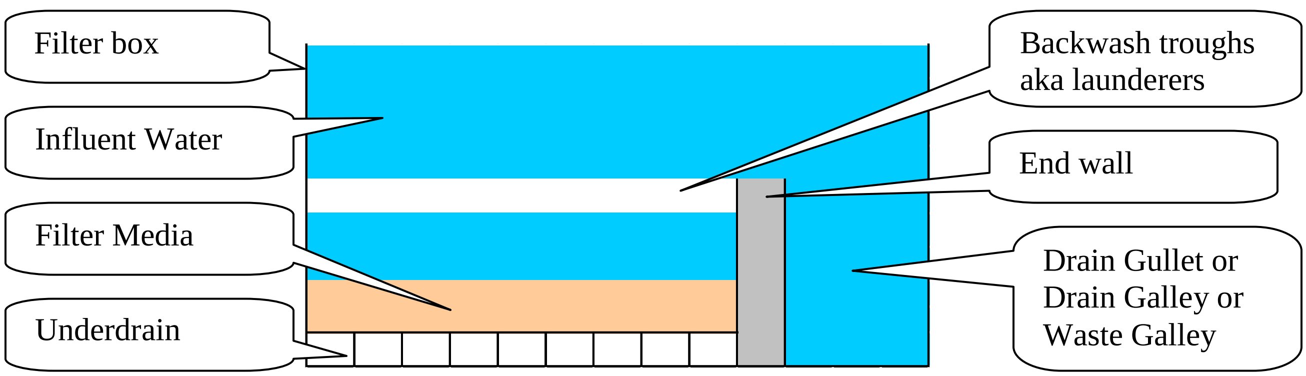

Figure 12: Typical Rapid, Dual Media, Multimedia Filter Construction

Slow Sand Filtration

As the name implies, slow sand filtration is slow. Filtration rates for granular media filtration are typically expressed at the number of gallons filtered per square foot of filter surface area per min, or gal/ft^2/min. A slow sand filter's filtration rate is approximately 0.05 gal/ft^2/min. Compare this to a rapid sand filter with a rate of 2 gal/ft^2/min., a dual media filter with a rate of 4-6 gal/ft^2/min.and a multimedia filter with a rate of 7-10 gal/ft^2/min. To filter one million gallons per day (695 gallons/min) then, a slow sand filter needs to have an area of 13,889 ft^2 – about one-third of an acre.

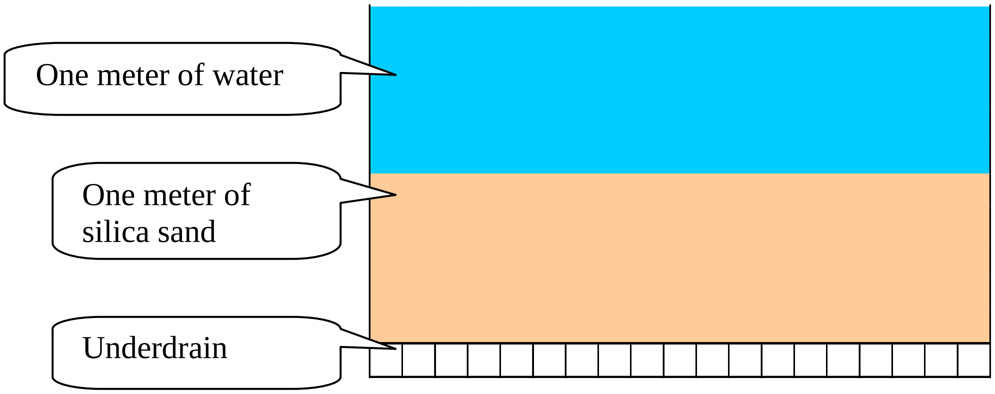

Figure 13: Typical Slow Sand Filter Construction

A slow sand filter is typically constructed in an earthen or concrete rectangular filter box. The filter may be uncovered, out of doors or enclosed in a building. Typically there is an underdrain system, about one meter of silica sand and one meter depth of water.

Figure 14: McMillan Reservoir Slow Sand Filter, Washington, D.C.

McMillan Reservoir Slow Sand Filter site in Washington, DC. as it exists today. Closed since 1986, the filters, constructed between 1903 and 1905, contained about 40 inches of sand and 12 inches of support gravel. Occupying almost 30 acres of total surface area, the capacity was approximately 80 million gallons per day – about 0.04 gallons/ft^2/minute. The filters were covered, just as shown. Water from the Potomac River was captured and allowed to settle in McMillan Reservoir. A coagulant was also added pre-filtration when the Potomac was very turbid. (Ref 41) Chlorination began in 1923. A modern filtration plant now occupies a portion of this site. It came on line in 1985. McMillan Reservoir is still in use with the new facility

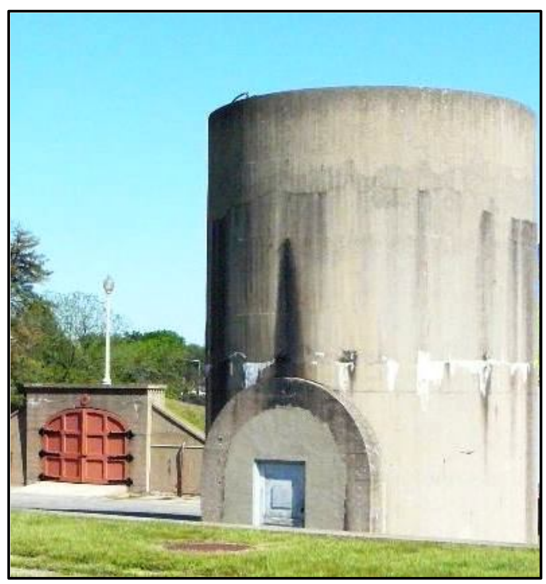

Figure 15: Concrete silo at McMillan Reservoir Site

There were many concrete silos at the facility used to store sand after it was removed from the slow sand filters and cleaned. The doors pictured at the left of the silo are access doors which were used to access the slow sand filters for maintenance.

While speed is not the forte of the slow sand filter, when properly applied good quality effluent is! The shallow depth of water on the sand permits oxygen to easily exist at the sand water interface. And when the filters were outdoors, sunlight also could penetrate to the sand water interface. These factors combined with the slow filter rate permit formation of a community of microorganisms at the sand-water interface. This community might include bacteria, viruses, protozoans, helminthes and others – a plethora of microorganisms. The biological activity forms a sticky mass that traps inorganic particulate matter but also removes much organic contamination. This mass – the autotrophic layer aka the *schmutzdecke* - typically confines the trapped matter to the top ½" to 3" of filter material. The *schmutzdecke* is similar in function to zooglea – the sticky biological mass on the surfaces of a wastewater trickling filter. (As wastewater 'trickles' over the trickling filter media, the zoogleal mass breaks down the organic matter. From the Greek z*oo*, animal and *gloea*, glue or clay.)

Cleaning is a matter of periodically scraping off the top layer containing the autotrophic layer. The sand removed is then washed (see silos above). The washed sand is stored for reuse. After several cleanings, some of the cleaned sand will be returned to the bed to return it to its original depth. Depending on the amount of water filtered and solids in the water the slow sand filter may need cleaning only once or twice per year.

Slow Sand Filtration	
Advantages	**Disadvantages**
Slow filtration rate for good filtration	Slow filtration rate
Formation of the autotrophic layer for biological cleaning	Requires large area
Needs little skill to operate. Very low technology suitable for small communities and developing regions of the world where manpower is more plentiful than technology needed for more sophisticated systems.	Periodically large amounts of time and labor are required to remove, clean and replace the sand
High quality effluent low in particulate, organic and biological contaminants	Requires a relatively good source water to minimize need for filter cleaning

Figure 16: Slow sand filtration advantages/disadvantages

Rapid Filters

In urban areas the slow sand filter simply occupies too much valuable real estate. Typical filtration rate for rapid sand filter is 2 gallons/ft^2 of filter area/min or 40 times the filtration speed of a slow sand filter. A slow sand filter requires over 13,000 ft^2 of surface per million gallons per day of capacity. A rapid sand filter provides the same flow with a surface area of only about 350 ft^2.

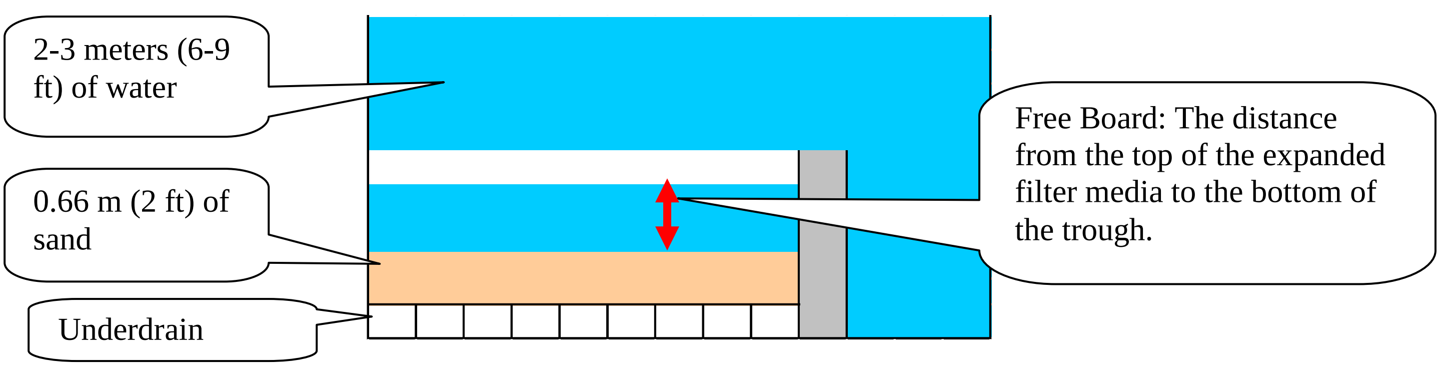

Figure 17: Typical Rapid Sand Filter Construction.
Depending on the type of underdrain used, support gravel between the sand and underdrain may be required.

The rapid sand filter meets the need for a higher filtration rate but as is always the case in the natural world – you can't get something for nothing. Filtration speed cannot be gained without giving up something else. Gaining filtration speed means giving up filtration power. The conditions existing in a slow sand filter for formation of the *schmutzdecke* do not exist in a rapid sand filter. And while it was sometimes necessary to use a chemical coagulant before a slow sand filter, it is almost always necessary to use a chemical coagulant before a rapid sand filter. The larger effective size of the filter sand and the higher filtration rate carries the solids deeper into the media, typically about 3" or more. Frequent cleaning – backwashing - is required. Depending of the amount of solids in the filter influent and flow rate backwashing can be required from every few hours to only once or twice a week but filter runs (the time from when a filter is started until the filtration process is terminated) for a rapid filter are typically about 24 hrs.

Rapid Sand Filtration	
Advantages	**Disadvantages**
Higher filtration rate	Not as efficient a filtration process
Requires small area	A biologically active layer does not form
Automated cleaning using a backwash	Needs frequent cleaning using significant amounts of treated water
Can handle a wider range and more variable water quality than a slow sand filter	Settling and use of a chemical coagulant is nearly always necessary.
Operation can become more automated and requires less man power.	Operation requires a higher level of skill and thus more training

Figure 18: Rapid sand filtration advantages/disadvantages

Note: Occasionally one may hear a water operator or manager refer to the presence of a *schmutzdecke* on a modern rapid filter (rapid sand, dual media or multimedia or even biologically active filters). Rapid filters do not have a *schmutzdecke* - biologically active layer - like that of a slow sand filter. There is no benefit to pointing out the error when the statement is made. The comment may be more a matter of careless terminology than incorrect understanding of the term. Let it go without comment. However, care should be taken to not make the same error in terminology.

Dual Media Filters

Dual media filters typically have approximately 18-24" of anthracite coal overlaying approximately 12" of silica sand. The anthracite having lower specific gravity (density) will 'float' on top of the higher specific gravity sand. Some mixing will inevitably occur but this also can be managed by proper selection of the uniformity coefficients and effective size of the respective media. One can also see the differences in specific gravity are not really very great. Thus, poor operation of the filter – initiating backwash at too high a rate, stopping backwash too quickly, interferes with free escape of backwash water from a wash water trough, etc. - can easily destroy the design integrity of the filter.

With careful management of the filter, the media will remain reasonably well stratified. Maintaining the initial design integrity and thus design performance of the filter depends on careful operation – especially management of the backwash process - to maintain media stratification. Filter backwash can be a very destructive operation. See Using Turbidimeters to Monitor Backwash below for a complete discussion of backwash management.

The more coarse (larger effective size) anthracite permits a higher filtration rate of 4-6 gallons/$ft^2$of filter area/minute. This also draws the solids more deeply into the filter media. Solids penetrate to nearly the sand/anthracite interface. The sand tends to provide a margin of safety to stop solids that may penetrate all the way to the sand. This penetration means a much greater volume of solids can be 'stored' in the dual media bed than in a rapid sand bed. Utilizing more of the filter bed for storage of solids permits longer filter runs. Operators may claim filter runs of 40, 60, 80 or even over 100 hours! "We sometimes wash just because we're feeling guilty." Very long filter runs may reduce the water needed to wash and associated power costs. These savings have very little merit unless the operators are able to prove with frequent (even better, continuous) water quality monitoring that the filter is providing the desired water quality.

Figure 19: Deep bed, Dual Media Filter

The filter design pictured contains 60" of anthracite over 12" of silica sand with a Leopold Type-S Underdrain with IMS cap. Thus, no support media are required under the sand.

Filtration speed and additional storage cannot be gained without giving up filtration power - again. Proper pretreatment with sedimentation, coagulation, flocculation and additional settling now is a necessity. And while it is a very good idea to use a chemical coagulant with a rapid sand filter, it is a must to use a chemical coagulant before a dual media filter.

Just because a filter is capable of a higher rate doesn't mean regulatory agencies will necessarily permit them to operate at a higher rate. It is common for regulatory agencies to require extensive study with additional monitoring to prove the higher filtration rate provides the same water quality throughout the filter run. Additional monitoring may include use of particle counters, additional microbiological sampling, use of microscopic particulate analysis (MPA), or a combination of additional monitoring procedures.

It should be apparent that as filtration rates increase, monitoring becomes more important and the level of training and skill required of the operations staff also increases.

Dual Media Filtration	
Advantages	**Disadvantages**
Higher filtration rate	Not as efficient a filtration process and additional monitoring may be required before a high filtration rate can be used.
Requires small area	A biologically active layer does not form
Automated cleaning using a backwash	Needs frequent cleaning using significant amounts of treated water
Can handle a wider range and more variable water quality than a rapid sand filter	Settling and use of a chemical coagulant is a must
Operation can become more automated and requires less man power.	Operation requires a higher level of skill and thus more training

Figure 20: Dual media filtration advantages/disadvantages

Multimedia Filters

Multimedia filters typically have approximately 18-24” of anthracite coal overlaying approximately 12” of silica sand and an additional layer of garnet (see Filter Media and Media Specifications, above), This combination of media permits a higher filtration rate of 7-10 gallons/$ft^2$of filter area/minute.

This penetration means a much greater volume of solids can be ‘stored’ in the multimedia bed than in a dual media bed. And, like dual media filters, claims of very long filter runs are common. There is nothing inherently wrong with long filter runs provided the length of the filter run is determined by filter performance (water quality) verified with continuous monitoring and not just arbitrary time or physical measurements like head loss.

Typically the layers of media in a multimedia filter are specified such that they tend to mix more than in a dual media filter. Interfaces between the layers of media will not be as distinct as with a dual media filter. The higher filtration rate and media combination permit the solids to penetrate more deeply than with a dual media bed. Storage capacity of the both the anthracite and sand layers are utilized. There is much less margin for error with a multimedia bed than with rapid sand or dual media beds. Poor operation of the filter can easily destroy the design integrity of the filter. And, poor operation can result in poor quality effluent.

Maintaining the initial design integrity and thus design performance of the filter depends on careful operation – especially management of the backwash process - to maintain media stratification. Filter backwash can be a very destructive operation. See “Using Turbidimeters to Monitor Backwash” below for a complete discussion of backwash management.

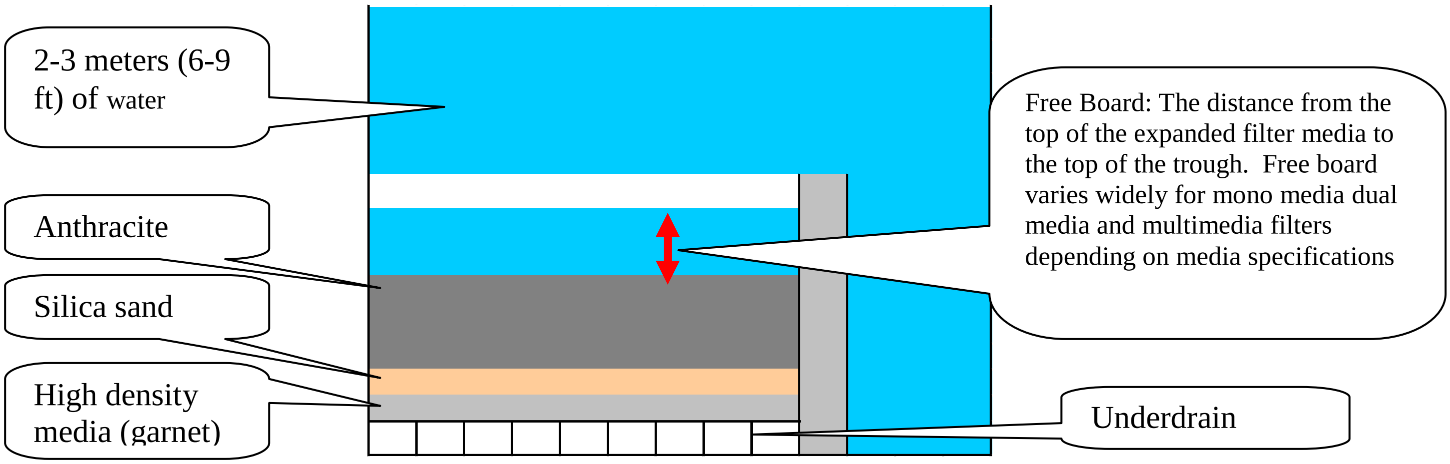

Figure 21: Multimedia filter configuration

Just as with dual media filtration, it is common for regulatory agencies to require extensive study to prove the higher filtration rate provides the same water quality throughout the filter run with additional monitoring. Additional monitoring may include use of particle counters, additional microbiological sampling, a microscopic particulate analysis (MPA), or a combination of additional monitoring procedures.

Automatic Backwash or Traveling Bridge Filter

Automatic Backwash or Traveling Bridge filters are another variation of rapid filters. They may also be referred to as continuous backwash filters. An automatic backwash filter is constructed of a number of individual cells in a single filter box. Each cell is an individual filter with a relatively shallow depth of filter media (typically about 12”) operating at a rate of 2-3 gal/ft^2/min. The filter media may be single media, dual media or multimedia. Dual or multi-media filters may have 18-24” total of media. This filter design is relatively low head and thus solids are maintained close to the surface of the media. Because of the shallow media depth, a backwash is required more often. Automatic backwash filters may be encountered in potable water, municipal wastewater (tertiary treatment) or industrial applications.

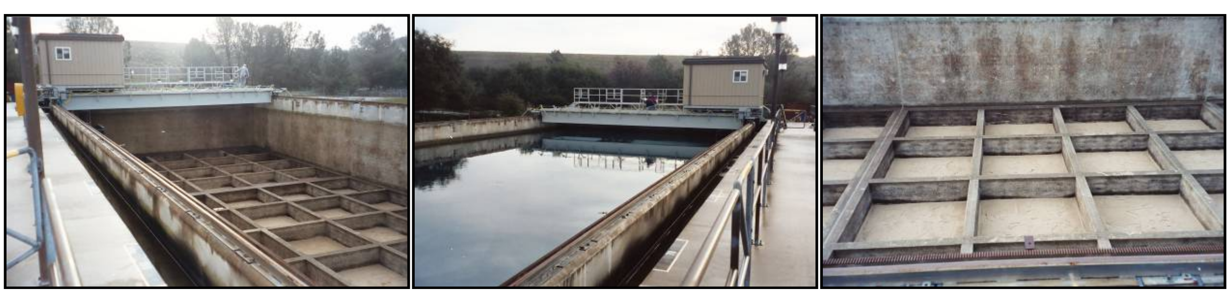

Figure 22: Traveling Bridge Filter

This unique design at the San Juan Water District (CA) water treatment plant employees an array of square cells rather than a rectangular cell array most commonly encountered (Figure 23). At this treatment plant, a Solitax TS sensor with SC100 controller is used to monitor the backwash.

As the headloss increases on an individual cell it is cleaned (backwashed) by the ‘traveling bridge’ (or in some designs just a moving hood) moving over the cell to be cleaned. A hood lowers over the cell to isolate it from the other cells. Flow is reversed only through that cell. When clean, the hood lifts and the cell returns to service. With an automatic backwash filter, less of the filtration capacity, as a percentage of total production, is taken out of service for cleaning. For example, one wastewater utility installed one 30-cell filter with a total capacity of approximately 500,000 gallons per day. At minimum if a traditional rapid sand filter had been used, two filters would have to be constructed so one could remain in service while the other was cleaned – i.e. 50% of the filtration capacity would be taken out of service for backwashing. With the 30-cell automatic backwash filter only $1/30^{th}$, less than 4%, of the filter is removed from service for cleaning. Other advantages may be lower initial construction costs.

Returning to the importance of multiple barriers, because of the shallow media depth, regulatory agencies may require increased monitoring of the process when these filter designs are used for potable water applications.

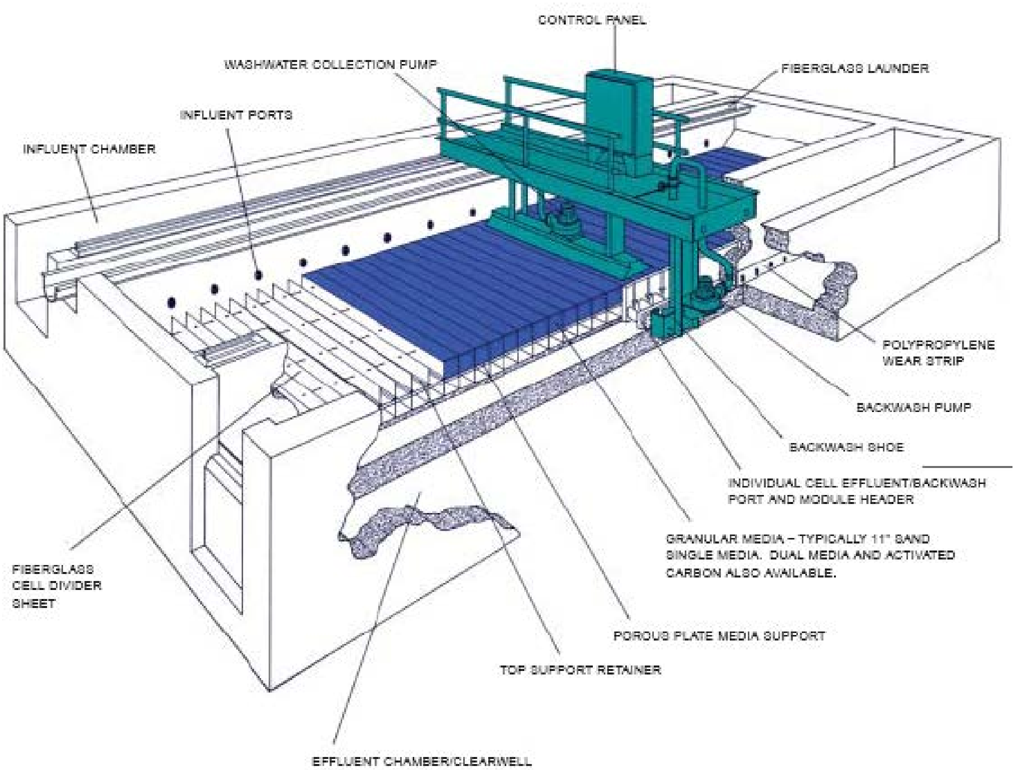

Figure 23: Automatic Backwash Filter

Diagram used with permission. Courtesy of Aqua-Aerobic Systems, Inc. Rockford, IL.

Pressure Filters

Pressure filters are nothing more than granular media filters in an enclosed vessel. And, rather than operating by the force of gravity the flow through the filter is typically created by pressure applied by a pump. Though, if sufficient hydraulic head is available, avoiding the complexity and cost of pumping is a bonus. Pressure filters may be horizontal cylinders from 8-15' in diameter and up to 60' long but typically are found in the 10-12' diameter and perhaps 20' in length. If the pressure filter is found in vertical configuration then a diameter of 10-12' and a height of 8-12' is common though some, as pictured on the right in Figure 24 may be much smaller. Media configurations can be most of the same options as the open gravity beds from rapid sand to multimedia or deep bed mono-media. Pressure filters are widely used for particular treatment objectives such as use of greensand (ion exchange) media for water softening and also special treatments for iron, manganese and/or arsenic removal.

Figure 24: Pressure Filters

Left: Horizontal pressure filter in Wisconsin. This particular filter and associated treatment scheme is designed for removal of iron, manganese and arsenic. Photo courtesy of Don Voight, Energenec, Inc, Cedarburg, WI.

Right: Three small vertical pressure filters manifolded together at a guess ranch in central Wyoming for a seasonal population of about 150 people. 1. Top of anthracite; 2. top of fine garnet; 3. top of coarse garnet.

What should be most obvious is, since a pressure filter is a closed vessel, any sort of visual monitoring of the condition of the filter will be very limited. Instrumental monitoring of water quality from a pressure filter is essential.

Direct Filtration

Direct filtration is a common variation of dual media (and sometimes multimedia) filtration. Direct filtration is appealing because it eliminates a great deal of equipment (hence cost and area required). Typically there is only limited settling at the treatment plant and after chemical addition there are not physical facilities for flocculation and settling after flocculation. As the name implies, raw water enters the plant, chemical coagulant and perhaps a filter aid are added. The only mixing/flocculation that occurs is in the pipe leading to the filter – thus direct filtration. Poor quality and/or highly variable source water is not a suitable candidate direct filtration. Direct filtration plants are typically fed from relatively large, stable reservoirs. Recalling the discussion at the first part of this document about the importance of a multiple barrier approach it is easy to see how many people are very skeptical of direct filtration as it removes several steps –barriers - in the process. When barriers are removed, the importance of careful monitoring is increased.

Biological Filtration

Biological filtration today refers to deliberate management of a modern rapid filter (typically dual media, multimedia or deep bed monomedia) to permit limited bio-growths within the media. One of the strengths of the slow sand filter was the biological treatment that occurred. Today's biological filtration with high rate filters is quite different. The interest in biological treatment results in large part from concerns with formation of disinfection by-products (DBPs) caused from the use of chlorine. To minimize formation of DBPs chlorination is being delayed until post filtration. Ozone, ultraviolet light or other non-sustainable (providing no residual) means of controlling microorganisms prior to filtration may be substituted. The result is viable organisms entering the filter bed attach to the media and through their metabolic processes reduce the organic matter that contributes to formation of DBPs. In addition to reduction or removal of DBPs, biological filters may also be beneficial in reduction of biodegradable organic carbon, metals (iron, manganese), ammonia, etc. Ideally, biological filtration is implemented with deliberate design of a new facility with the biological filters following conventional filters. Often times there are not the time, space or budget to do this and it is often cost prohibitive to retrofit existing facilities in this way. So, existing filters are "converted" to biological filters by simply stopping prechlorination. This may result in increase turbidity and particle counts in the filter effluent as the biomass sloughs. One customer reported they had been cleaning their 1720C turbidimeters about once per month with little effort. After conversion to biological filtration they needed to clean the 1720C's weekly with more effort!

Control of Filtration

Flow through most granular media filters is simply by gravity - differential head pressure. As water flows through the media some of the pressure (head) must be used to overcome the friction loss (headloss) created by the media, other filter appurtances (under drains, etc.) and accumulated solids. As the water flows through the column of media and solids are trapped, the headloss will increase until the headloss is too great and then the filter must be cleaned. Headloss also can be created by entrained air becoming trapped in the filter bed and thus "air binding" the filter bed. Measurement of headloss is typically by use of a mechanical differential pressure gauge or electronic or pneumatic differential pressure sensors/transmitters.

Caution: When trying to monitor filter effluent it is tempting to use the same tap as is being used to measure differential pressure. That is almost always a BAD idea as it will cause erroneous differential pressure measurements. Rather than taking a chance, use a different sample tap to get a sample for a turbidimeter, pH meter, particle counter, etc.

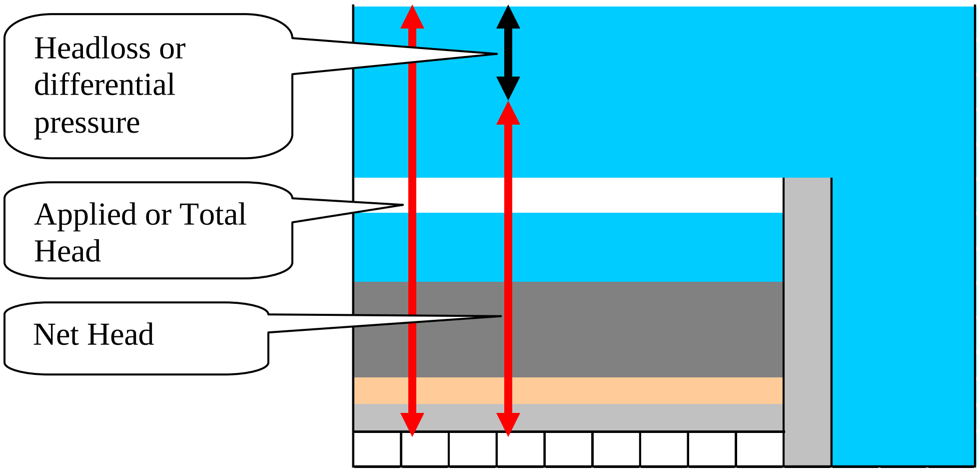

Figure 25: Filter head terminology

Filtration control can be accomplished a number of ways. Three of the most common are

- Constant rate –
  - Effluent valve modulated - The influent head remains constant and the filter effluent valve is opened as needed to maintain a set flow rate.
  - Applied head is modulated - In some designs, the effluent valve may be held constant and the applied head increased or decreased to maintain constant flow.
  - One can see that as the head differential increases there is a greater potential for pulling (pushing) solids more deeply into the bed until finally the bed becomes totally plugged or until solids begin to breakthrough.
  - Cleaning is triggered based on headloss or number of hours of filtration.

- Declining rate - The influent head remains constant and the filter effluent valve kept in a fixed position. One can see that as the headloss increases the flow decreases to a set point at which the filter is taken off line and cleaned. In this scheme it is less likely solids will breakthrough.
- Flow paced – The filter “rides” on demand. The total head typically is held constant and the filter effluent valve is automatically modulated to match demand requirements. The filter is taken off line after a certain headloss is reached or a preset number of hours are accumulated.

Most machines have the longest life, best performance, most consistent quality if operated in steady conditions. Gravity granular media filters are no exception. Flow pacing is very appealing but if not closely monitored can result in highly variable water quality. Headloss is a function of both the flow rate and the solids accumulation. A clean bed operated at a high filter rate will have a greater headloss than the same bed operated at a lower rate.

Similarly, a dirty bed will appear producing acceptable effluent quality at a lower flow rate. Here in lies the problem. Suppose a flow-paced filter with a large number of hours is operated at a low flow due to low demand. Thus the headloss is low. Then system demand increases so the filter automatically is called on to increase flow. This sudden demand creates a corresponding sudden increase in differential pressure (headloss, rapid increase in hydraulic gradient) thus driving accumulated solids deep into and possibly through the bed resulting in breakthrough and loss of water quality.

Some demand-paced filters may automatically start and stop several times during a filter run, perhaps multiple times per day. If a filter is stopped after a period of use and then restarted, the increase in hydraulic gradient when the filter is returned to service may drive accumulated solids through the bed. Some regulatory agencies may require that a filter taken out of service for any reason, even though it had minimal hours of filter run, to be backwashed before being placed back into service or by continuous and grab sample monitoring must prove no harm to water quality. Operators and managers may object strenuously to these requirements. It is in fact not unreasonable. See the very reasonable policy from the State of North Carolina (Ref 22):

<u>POLICY STATEMENT</u>

SURFACE WATER TREATMENT FACILITIES
REF: Filter Operations

North Carolina Division of Environmental Health
Public Water Supply Section
W.E. Venrick, PE, Chief

July 15, 1994

1. Filter operations shall not exceed ninety-six (96) hours of continuous service between backwash cycles.

2. Filter backwash procedures should include surface sweeps and/or air scour mechanisms and filter-to-waste function capabilities.

3. Filter media should be physically evaluated at least annually for fouling, scaling, or loss of bed depth. Damaged media should be cleaned or removed and new filter media added as necessary to restore the volume to original specifications. The entire unit must be disinfected and found to be free of coliform bacteria prior to being placed into service.

4. Filters that have been out of operation <u>two</u> (2) or more hours shall be backwashed prior to reinstatement to service. (Filter-to-waste may be allowed instead of backwashing if the water utility can demonstrate quality control through measurements for turbidity, chlorine residual, pH, and particle counts in the filtered water. Filter-to-waste operation should be at the same flow rate as normal filter operations and continue at least two times the theoretical detention time for filter unit.)

No matter what the filter control scheme is – constant rate, flow paced, declining rate – varying the filter flow for any reason jeopardizes water quality. In smaller treatment plants the demand may be such that the plant runs only a few hours per day or even only a few hours per week. Every time the plant stops all steady state conditions are lost including balance of chemical feeds. And once the plant restarts all of the physical and chemical conditions must be reestablished before good quality effluent is attained – including filter effluent quality. (See paragraph 4 of the North Carolina policy, above.)

The bottom line is this:

- Best water quality will be maintained if the entire treatment process is maintained at a constant rate with continuous monitoring.
- Maintaining water quality with variable flow rates or start/stop operations is very difficult and requires very good monitoring.

Backwashing

Rapid filters – rapid sand, dual media and multimedia beds – require periodic cleaning to remove accumulated solids. During the cleaning cycle, or backwash, the flow is reversed and a flow rate of 13-20 gals/ft^2/min is forced back through the bed to remove accumulated solids. During this process, the bed expands becoming fluid to allow release of accumulated solids. The rate of backwash depends on a number of factors related to design of the bed and also water temperature. Typically, the backwash rate will be in the range of 15-17 gals/ft^2/min. The consulting engineer responsible for the plant design or the filtration equipment provider typically will provide a curve for determining the proper backwash rate based on the particular filter design. The following figure is an example of the curve.

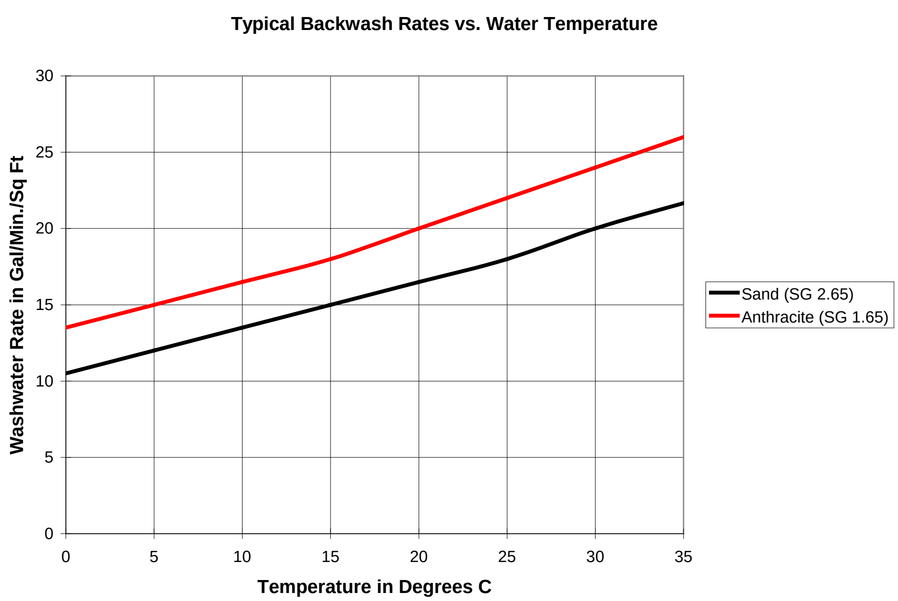

Figure 26: Backwash rates vs. Water Temperature

Backwashing is a potentially destructive process if not properly managed. If the process is initiated too quickly and/or at too high a flow rate and/or terminated too quickly, the bed can be severely damaged. Inadequate backwashing can create nearly as many problems. Leaving too many solids in the bed can lead, at best, to short filter runs and at worst to more severe problems like mud balls and even cementing entire areas of the bed.

• **<u>Under washing</u>** o Accumulation of solids in the bed o Mud balls o "Cementing" portions of the bed o Migration of filter media o Poor quality effluent water o Short filter runs	• **<u>Over washing</u>** o Excess water use o Excess power use o Short filter runs o Loss of filter media o Ineffective filter ripening

Figure 27: Adverse Effects of Improper Backwashing

Figure 28: Anthracite Loss Due To Backwash

(A)- a sludge drying bed for backwash water. (B)- a close up of the dried sludge showing a significant portion of the solids are anthracite filter media! This amount of lost media is an indication of poor filter design or, more likely, improper operation – i.e. washing at too high a rate, using surface washing (surface sweeps) too long, improper media depth, or a variety of other reasons. (C)- photo from another treatment plant backwash sludge drying bed showing no anthracite filter media loss.

Determining when to backwash typically involves monitoring filter headloss (differential pressure) and/or operating hours. During backwash, the backwash rate, backwash time, and backwash water use are monitored. Operators may also mention monitoring bed expansion, free board and filter rise rate.

- Bed Expansion – During backwashing flow is reversed and the flow rate gradually increases to about 15 gallons/ft^2/minute. At this rate the media are fluidized or expanded. Depending on the particular media specification that expansion may be nearly 100% of the unexpanded media – that is if there is 18" of anthracite, during backwash it may expand to as much as 36". This expansion permits solids trapped within the media to be released and carried out. It was common 40 years or more ago to measure bed expansion with sensors or simply sight windows. Today at least one company sells a bed expansion monitor. In reality the need to monitor actual expansion of the bed is very infrequent, certainly not on a daily, weekly or even monthly basis. It's designed into the system. Perhaps once or twice a year one can check bed expansion just to confirm integrity of system. Simple tools are sufficient. No fancy electronic gadget is required.

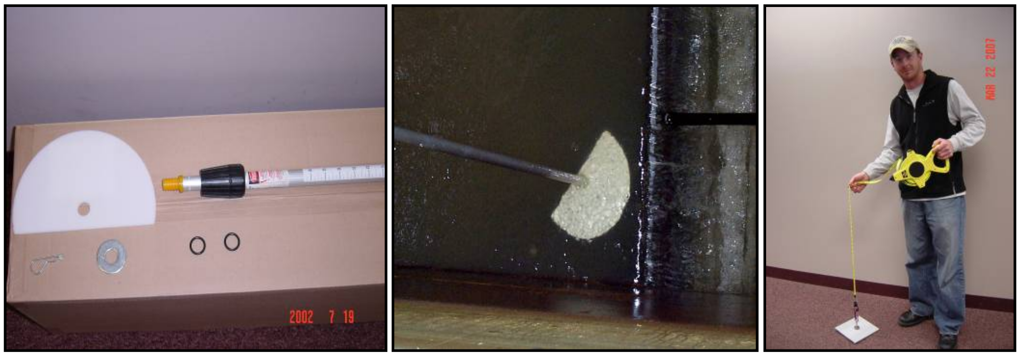

Figure 29: Measurement of filter bed expansion

These photos illustrate simple bed expansion monitoring tools used by The Pennsylvania Department of Environmental Protection. These homemade, relatively inexpensive tools for monitoring bed expansion are used during the periodic performance review of water filter operations in Pennsylvania. The devices are lowered until they are under the expanded media surface and then the depth is measured.

These tools are essentially variations of an old device called a Secchi Disk used for years to determine clarity of lakes and even in the ocean. While its use has diminished they are still sometimes used in environmental studies. Photos used with permission of Ed Chescattie PADEP.

- Filter Rise Rate – Filter rise rate is a rough measure of the filter backwash rate. At a backwash rate of 15 gallons/ft^2/minute, with the drain valve closed, the water level in a filter will rise 2 feet per minute. Thus is an operator wishes to check the backwash flow rate meters/gauges/SCADA reading, they can set the rate to 15 gallons/ft^2/minute, close the drain valve and simply time the time to rise 2 feet – perhaps using one of the nifty measuring tools pictured above and a stop watch.

- Free Board – Free Board is the distance from the top of the expanded media to the bottom of the backwash trough or launderer. Since the media expands (is fluidized) during backwash, the top of the trough must be high enough so that media are not washed out with the backwash.

- Surface Wash – Many rapid filters are equipped with rotating arms (surface wash arms, surface sweeps) or less commonly fixed position nozzles used to break up solids accumulated near the surface of the filter media. Surface washing typically precedes the backwash and is normally terminated before the full backwash rate is reached. The flow rate for surface wash typically is about 2 gal/ft^2/min. This flow is additive to the backwash rate. Thus, if the surface wash is operated along with backwash, the total flow – backwash plus surface wash must not exceed the maximum flow for the water temperature. For example, if the maximum backwash rate at a water temperature of 50ºF is 15 gallons/ft^2/min, then the total of backwash rate and surface wash rate must not exceed 15 gal/ft^2/min.

- Air Wash – aka Air Scrub and Air Scour – As with surface washing, the purpose of air washing or air scour is to assist with removal of solids from a filter bed. Most modern systems using air wash introduce the air via the underdrain system utilizing filter under drains specifically designed for both water and air distribution.

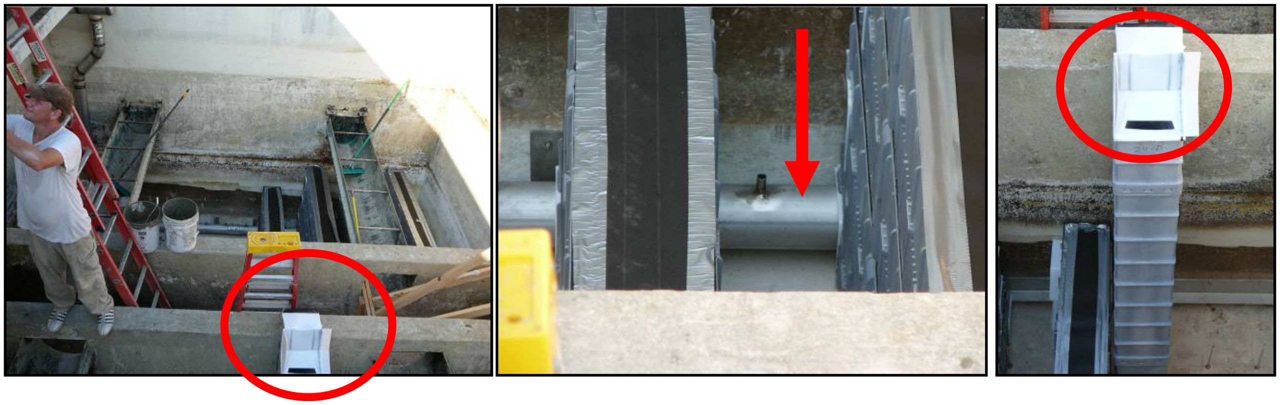

Figure 30: Leopold Type-S under drains with IMS cap during installation

The photo array shows Leopold Type-S under drains with IMS cap during installation. The individual blocks are first assembled together to the appropriate overall length (right photo) and the edges taped off to protect them. The notch (red circled area in left and right photos) permits the air wash pipe (arrow, center photo) to pass under the block. Once all the blocks are in place, space between the rows of blocks is filled with grout.

Backwashing is an expensive process. In a well-operated filter system, backwashing may consume 1-3% of the filter's production, typically around 2%. Assume a filter has a capacity of 2 MGD and operates for 48 hours between backwashes. The amount of water used to backwash would be approximately 2% of 4 MG or 80,000 gallons. If the water is sold by the utility for $2.00/thousand gallons (a very reasonable number, in many areas the price is much higher), each filter wash costs at least $160 in otherwise saleable product.

Some operators and utility managers will argue that the water is not lost – "it is all recycled and therefore does not cost us much at all." In fact, those 80,000 gallons are approximately an hour of production – 4% of the daily capacity of the filter. This is not a trivial amount in water-short regions, during periods of high demand or in drought conditions.

There are costs of backwashing:

1. Water used for washing if recycled, must be treated again. If the water is not recycled backwashing results in increased need for raw water resources.

2. The water used for washing must be pumped. If the wash water is recovered, it typically goes through one or more stages of pumping and settling before it is returned.

3. Water used for washing is not available for sale. An amount equal to the wash water volume must be treated or retreated.

Water operators typically monitor backwashing either visually or on the basis of a preset time.

1. If it is done by time, at least it is consistent. Though it could be consistently too much water or too little. Neither is good.

2. If it is controlled visually, every operator will have a different idea of what constitutes clean and thus every wash will be different. Each operator making an independent judgment results in inconsistent operation at best.

Using a turbidimeter to monitor backwash has the benefits of consistency and a thorough wash based on measurement rather than on a fixed time or the subjective opinion of an individual.

The Solitax T-Line and TS-Line sensors can be applied for monitoring backwash.

Backwash Monitoring Considerations

The amount of time saved will be on the order of a few minutes at most. In some cases, less than a minute might be saved. Yet, even these small amounts of time can add up to significant savings over time. Rapid response time is critical in achieving full benefit. A submersible design, like the Solitax is necessary to achieve nearly instantaneous measurement.

Measurement must be within the filter, preferably in the backwash trough to achieve optimal saving and for ease of access. It is important to install the sensor in the trough in such a way as to not interfere with the free escape of water from the trough (it must not change the hydraulic grade line of the water in the trough). Any sort of dam (weir) to create a pool of water in the trough can significantly alter the free discharge of backwash water from the filter and cause serious damage to the filter media by encouraging excess flow in unrestricted troughs (and surrounding media) and lower flow in the restricted trough (and the surrounding media). This differential flow can cause the fluidized media to migrate within the bed thus destroying the proper stratification of the media.

Mounting the probe in a pipe downstream of the filter and/or to manifold a number of filters to the same sensor may well create too much delay in measurement. This delay will eliminate any possible benefit that could otherwise be gained. In-pipe or manifold mounting should be used only as a last resort.

Because time savings from monitoring backwash may be only a minute or so per wash, rapid response is critical and thus the needs to be mounted as closely as possible to the sample – ideally directly in the backwash trough.

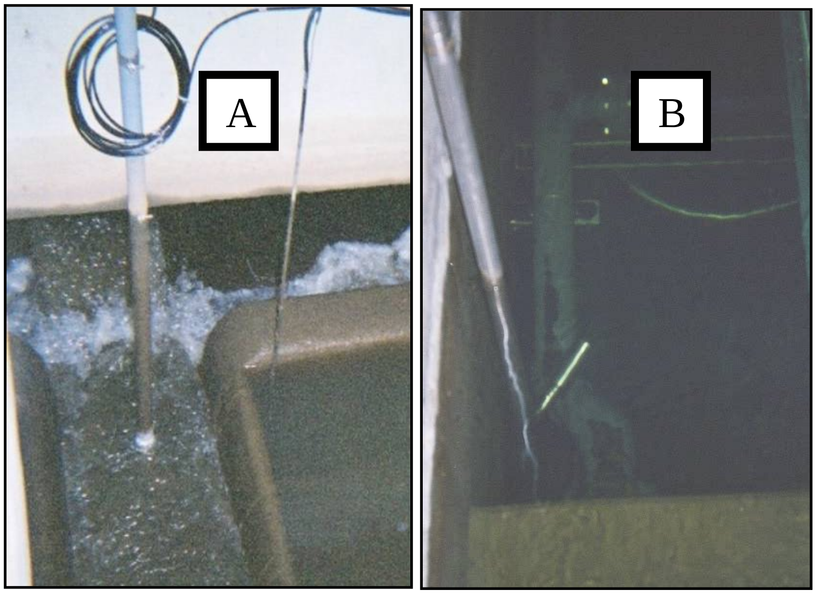

Figure 31: Backwash sensor mounting

Left (A): To provide rapid response it is best to mount the sensor in the wash trough. Water in the wash trough is fairly representative of the wash water from the filter in general. Right (B): Mounting the sensor in the filter bed, as shown is non representative as it monitors only the water in that one corner of the bed. That said, using the second input on the SC100, it is a good idea to use a second sensor (as illustrated in B) and probe the corners of the bed to detect localized problems.

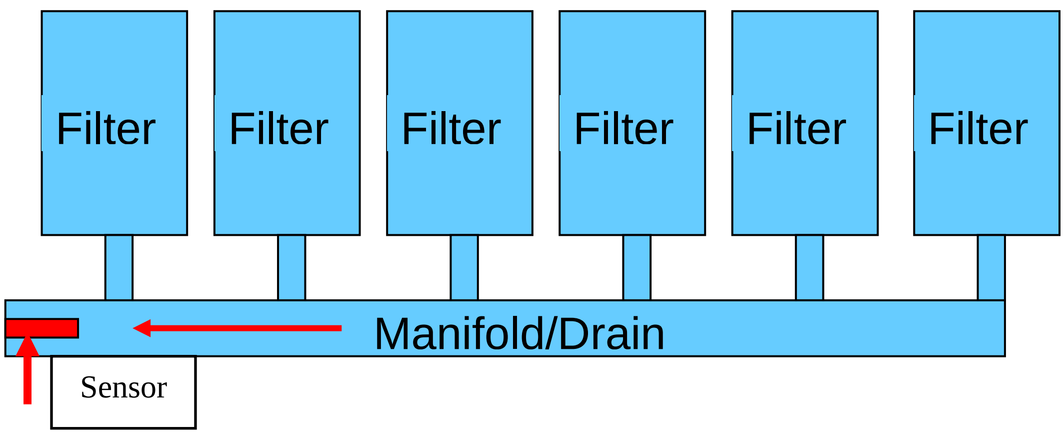

Figure 32: Manifold mounting of sensor.

Manifold mounting of the sensor to monitor multiple filters should be avoided. The time delay that results will make it nearly impossible to achieve any kind of time savings.

Time will not always be saved – initially. Visual or time-based judgment of the backwash period can also lead to under washing. As indicated earlier, serious problems can result from ineffective cleaning of the filter bed. Using a Solitax to monitor the backwashing process will help to restore the bed to good condition and then maintain it in good condition. Invariably, this will lead to cost savings.

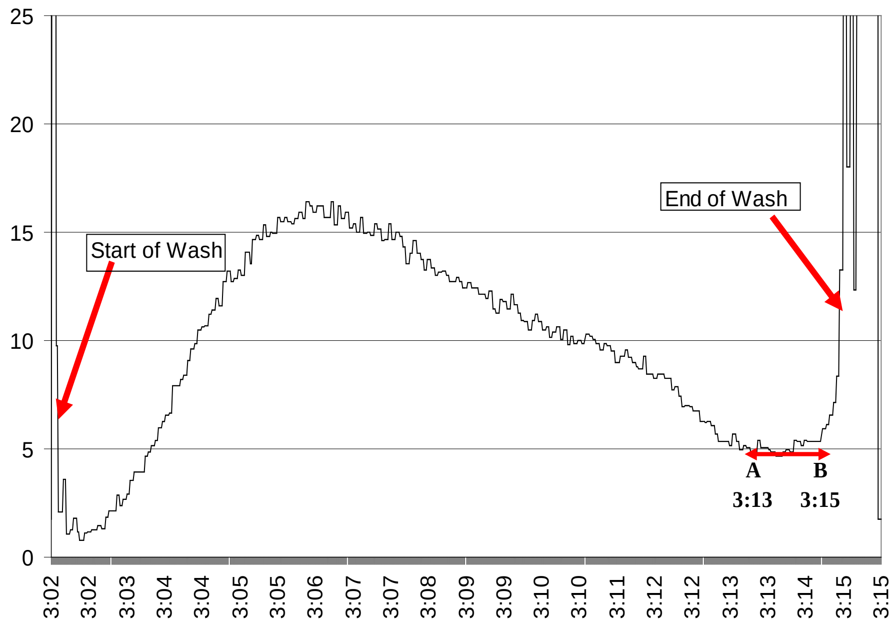

Figure 33: Backwash Curve

The backwash illustrated started at 3:02 and continued until approximately 3:15. Note that the turbidity became nearly constant at about 3:13 but was not terminated until approximately 3:15. Thus over 2 minutes of backwash time, water and energy could have been saved. Assuming a small filter with an area of 300 ft^2 (15'x20') and a wash rate of 15 gal./ft^2/min, that means savings could have been achieved of about 9000 gallons of wash water plus all the associated costs of pumping, treatment and retreatment.

Calculations of Savings Possible by Using Turbidimeters to Monitor Backwash

Properly applied, using a turbidimeter (Solitax) will save nearly any water treatment plant with conventional filtration a significant amount of money. In many cases, the cost to purchase and install the turbidimeters can be recovered in less than a year. Unfortunately, calculation of the cost savings is not always understood. A description of how to account for the cost follows. There will be unique aspects of nearly every operation one has to consider.

1. Calculate the direct and indirect dollar savings which can be achieved by using less wash water:

$$\frac{\text{\$ Cost of Operation}}{\text{1000 Gallons}} \times \frac{\text{1000 Gallons Saved}}{\text{Backwash cycle}} = \frac{\text{\$ Saved}}{\text{Backwash cycle}}$$

Where Cost of Operation per 1000 gallons is:

$$\frac{\text{Total Annual Budget}}{\text{1000 Gallons Produced Annually}} = \frac{\text{Cost of Operation}}{\text{1000 Gallons}}$$

The total annual budget is the expenditure for treatment plant operations – the bottom-line - including: salaries, benefits, utilities, chemicals, consulting fees, debt service, maintenance, depreciation and capital expenses.

And, 1000 Gallons saved per Backwash cycle is:

$$\frac{\text{1000 Gallons}}{\text{Minute}} \text{ (at maximum wash rate)} \times \frac{\text{Minutes Saved}}{\text{Backwash cycle}} = \frac{\text{1000 Gallons Saved}}{\text{Backwash Cycle}}$$

And, dollars saved per backwash is:

$$\frac{\text{1000 gallons saved}}{\text{Backwash}} \times \frac{\text{cost of operation}}{\text{1000 gallons}} = \text{\$ saved per backwash}$$

2. Calculate the dollar savings of electrical power. The power consumption of *every pump (and blower if using air wash)* used in the backwashing process must be calculated. Be sure to include the main backwash pump, surface wash pump, wastewater return pump and any other pumps used in the process. Treatment plants using air scour and/or air wash also will need to calculate savings in blower operation. Since the surface wash pump generally is used only at the beginning of a backwash cycle, shortened backwash cycles may have no effect on operation of the surface wash pump. However, some water plants will use the surface wash throughout the backwash and its power use must then be accounted for.

   Calculate the power for each pump and blower used as follows:

$$\text{KW Used} \times \frac{\text{Hours of Pumping}}{\text{Backwash}} \times \frac{\text{Dollars}}{\text{KWH}} = \frac{\text{Dollars}}{\text{Backwash}}$$

   Where KW = Kilowatts – the apparent power used by the pump or blower, sometimes indicated as KVA on the motor name plate or can be calculated by multiplying the rated voltage by the running amps.

   And, KWH = Kilowatt-hours. This is the basis most power companies charge for power and is one kilowatt of demand for one hour. A telephone call to the power company will be sufficient to determine the cost per KWH. $0.04 to $0.10 would be typical around the US depending on whether the power is from gas, coal, wind or hydroelectric operations.

Many other considerations are not enumerated here. Cutting the backwash saves hours of pump operation per year, which will translate to longer pump life and decreased pump maintenance costs. When a treatment plant has a regular maintenance schedule based on hours of operation, these costs can be quantified and should be included.

Calculate the dollar savings based on reduced labor. This is often the toughest concept to sell. Many municipal utilities assume labor is free, “Heck, the operator is here for eight hours anyway, I can’t possibly save any labor cutting 1.5 minutes from backwash." Labor is not free. The time saved can be utilized doing something else. For a complete discussion of how to calculate the backwash savings cost, with a worked out example, see Ref 16. An completed example is illustrated in Figure 34. The example was completed with an auto-calculating Excel workbook that is available as a complement to the document cited in Reference 16.

Figure 34: Calculation of Backwash Savings Worksheet

Summary of direct savings:

1 Savings from using less water:
- a. Value of water saved $__________
- b. Saving of retreatment cost $__________

Total $__________

2 Savings in power costs
- a. Backwash pump $__________
- b. Surface wash pump $__________
- c. Waste return pump $__________
- d. Other pump $__________
- e. Blower $__________

Total $__________

3. Savings in labor $__________

Total $__________

Total Direct Annual Savings $_________

Indirect Annual Savings

Revenue Generated from water saved $_________

Water saved per year from treatment or retreatment ___________ gallons

Calculate Potential Savings in Backwash			
1	**Calculate cost per thousand gallons**		Notes:
a	Total Annual Budget	$3,000,000.00	Include salaries, benefits, debt service, capital expenses, maintenance - the bottom line.
	Average daily production in gallons	15,000,000	
b	1000's of gallons produced annually	5,475,000	
	Cost of Operation per 1000 gallons =	$0.55	
2	**Calculate water savings per backwash**		
a	Backwash flow rate in 1000's/min	5.3	5,500 gal/min = 5.5 K gal/min
b	Enter minutes saved in backwash	2	
	1000's of Gallons saved per backwash	10.6	
3	**Calculate dollar savings per backwash**		
	1000's of gallons saved (line B10 above)	10.6	
	Cost of Operation per 1000 gallons (line C5 above)	$0.55	
	Dollars saved per backwash	$5.81	
4	**Calculate annual savings in backwash**		
	Number of Filters	8	
	Average Filter run in hours	60	
	Average number of backwashes per year	1169	
	Cost savings per year	$6,787.10	
	Water savings per year in gallons	12386453	
	Calculate annual savings in retreatment/replacement water treatment costs	$6,787.10	Equal to line C22
5	**Calculate Pumping Cost for each pump**		
	Backwash Pump		
	KVA (KW)	30	From motor name plate
	Minutes of pumping saved per backwash	2.00	
	Hours of pumping saved per year	38.95	
	Cost in $ per KWH	$0.078	
	Dollars saved per backwash	$0.078	
	Dollars saved per year	$91.15	
	Surface Wash Pump		
	KVA (KW)	22	From motor name plate
	Minutes of pumping saved per backwash	1.00	
	Hours of pumping saved per year	19.48	
	Cost in $ per KWH	$0.078	
	Dollars saved per backwash	$0.029	
	Dollars saved per year	$33.42	
	Backwash Return Pump		
	KVA (KW)	22	From motor name plate
	Minutes of pumping saved per backwash	5.00	
	Hours of pumping saved per year	97.38	
	Cost in $ per KWH	$0.078	
	Dollars saved per backwash	$0.143	
	Dollars saved per year	$167.10	
	Total Annual Savings in Pumping Costs	$291.67	
	Total Annual Savings in Pumping Hours	155.80	
6	**Calculate Savings in Labor**		
	Enter the average hourly pay rate in dol	$16.00	
	Average annual labor savings in hours	38.95	
	Average annual labor savings in dollars	$623.22	
7	**Total Annual Savings in operations (Dollars)**	$14,489.08	
	Annual Savings in Water (Gallons)	12,386,453	
8	**Calculate Salable Value of Water Saved**		
	Price per 1000 gallons to the customer	$2.25	
	Salable Value of Water Saved	$27,869.52	

Figure 35: Example of a backwash savings calculation

1. Coagulation and Flocculation

Chemical treatment typically is applied prior to filtration to enhance the ability of the filters to remove particles. Two steps typically are employed, coagulation and flocculation. Today coagulation is seen as a process to neutralize charges and also to form a gelatinous mass to trap (or bridge) particles thus forming a mass large enough to settle or be trapped in the filter. A comprehensive discussion of coagulation and flocculation is outside the scope of this paper but a simplistic description below will suffice to demonstrate the importance to filtration.

Particles in water smaller than about 10 microns are difficult to remove by simple settling or filtration – especially those particles smaller than 1 micron – colloids.

Particle Size Vs. Settling Rate Table

(Assuming specific gravity of 2.65)

Particle Diameter, mm	Example	Total Surface Area		Mass, mg per particle*	Total Number of Particles	Time to Settle One Ft.**	Time to Settle One Meter**
		Metric	English				
10	Gravel	3.1419 cm^2	0.487 $in.^2$	1.3868E+03	1.E+00	0.3 sec	0.98 sec
1	Coarse Sand	31.4193 cm^2	4.87 $in.^2$	1.3868E+00	1.E+03	3.0 sec	9.84 sec
0.1	Fine Sand	314.1929 cm^2	48.7 $in.^2$	1.3868E-03	1.E+06	38 sec.	2.08 min
0.01	Silt	0.3140 m^2	3.38 $ft.^2$	1.3868E-06	1.E+09	33 min	1.80 hrs
0.001	Bacteria	3.1340 m^2	33.7 $ft.^2$	1.3868E-09	1.E+12	55 hrs	7.52 days
0.0001	Colloidal	31.7728 m^2	38 yd^2	1.3868E-12	1.E+15	230 days	2.07 yrs
0.00001	Colloidal	2832.7995 m^2	0.7 acres	1.3868E-15	1.E+18	6.3 yrs	20.66 yrs
0.000001	Colloidal	28327.99 m^2	7.0 acres	1.3868E-18	1.E+21	63 yrs	206.64 yrs

*** Note: Total mass in the system remains constant at 1.386 grams or 1,386 mg**

****Assumes completely quiescent conditions**

Figure 36: Table of Particle Size vs. Settling Rate

Adapted from Water Quality and Treatment, 3rd ed. The left column indicates starting with a single particle 10 mm in diameter. The table then illustrates the resulting change in particle size, total surface area, number of particles and settling time as the initial particle is ground up to make smaller particles. One particle 10mm in diameter becomes 10^{12} particles by the time it is ground to a size of 0.001 mm (1µm). Notice also while the mass per unit particle decreases, the total mass in the system remains unchanged. Clearly, there is not necessarily any correlation between particle counts and mass, turbidity and mass or between particle counts and turbidity!

Colloids are stable in water because they have a very large surface area relative to their mass and they have a static electric charge. Most particles in water have a negative charge. Static charge is entirely a surface effect thus the greater the surface area relative to the particle mass, the greater the effect of the charge. The particles cannot agglomerate into larger particle and settle because they repel one another. The purpose of adding a coagulant is to neutralize the charge. Aluminum salts contribute trivalent aluminum ions, Al^{+3}, while the iron salts contribute trivalent iron ions, Fe^{+3}. The trivalent metallic ions are effective in charge neutralization. Trivalent ions such at Al^{+3} and Fe^{+3} are 1000X more effective a monovalent ion, i.e. Na^{+1}, and 100 times more effective in charge neutralization that a bivalent ion, i.e. Ca^{+2} (Schulze-Hardy Rule). After a short time the ions form hydroxide gels. The gels then can trap particles or bridge between particles creating a floc that may settle or at least be large enough to be removed by filtration. Charge neutralization occurs very rapidly.

Flocculation – gentle mixing to encourage collision of particles and the gel to form a larger mass may be carried out for a half hour or more. The flocculation process is then followed by settling. Particles not removed by settling then are removed by filtration.

2. Measurement of Aluminum and Iron

When iron or aluminum chemicals are used as coagulants the metal should be measured in the raw water, filter influent and filter effluent. The iron or aluminum in the filter effluent should be no more than, preferably less than, the raw water and filter influent concentrations. For most water the FerroVer® 3 Iron Reagent (1, 10 Phenanthroline method) for total iron is appropriate for iron and the AluVer 3® Aluminum Reagent (Aluminon method) is appropriate for aluminum. For low level iron use the FerroZine™ Iron Reagent and for low level aluminum the Eriochrome Cyanide R (ECR) method (may not be used with DR800's). When measuring aluminum, fluoride interferes. All aluminum measurements must be corrected for fluoride interference. Once the fluoride is measured, use the fluoride interference correction chart in the method. The correction chart for the AluVer 3 and the ECR method are different. Take care to use the correct chart.

Use the SPADNS 2 (arsenic-free) or fluoride electrode to measure fluoride. Fluoride must be measured regardless of whether or not the utility fluoridates. Fluoride exists naturally in every water source on earth – ground or surface. Natural fluoride concentration may range from 0.1 to over 10 mg/l.

Iron and Aluminum Reagents				**Instrument***
Test	Reagent	Range – mg/l	Cat. No.	
Iron (total)	FerroVer PP	0.02 - 3.00	21057-69	C, S, PC
	FerroVer AV	0.02 - 3.00	25070-25	C, S, PC
Iron	FerroZine	0.009 - 1.400	2301-66	C**, S
Aluminum	AluVer 3	0.008 - 0.800	22420-00	C, S, PC
Aluminum	ECR	0.002 - 0.250	26037-00	S
*** PC – Pocket Colorimeter C – colorimeter S – spectrophotometer **DR/890**				

Figure 37:   Iron and Aluminum Reagents

3. The Jar Test

The jar test is the most basic test for control of filtration and completed with a multiple stirrer such as the Phipps Bird.

Figure 38: Jar test apparatus

Phipps Bird 6-Place Programmable Multiple Stirrer with 1-liter round glass beakers. A 6- and 4-place nonprogrammable and 4-place programmable are also available.

The jar test can be performed with round jars, square jars, ½ L jars, 1 L jars, 2 L Wagner Jars or for that matter, mayonnaise jars.

- Features the customer should look for are a back panel, typically black to view the water in the jars and a white or lighted base.
- You may encounter Hach brand multiple stirrers that used ½ liter jars, it was discontinued several years ago. It had no lighted base but reflective white plates under the jars.
- The Phipps Bird has a fluorescent lighted base under the jars.
- When using the lighted base, the light should be left off except when the floc formation or settling is observed. The lighted base will generate enough heat to create convection currents. Changing the temperature of the water during coagulation and flocculation will lead to non-representative floc formation and the convection currents will interfere with settling.

Figure 39: Wagner™ Jar with Phipps Bird Multiple Stirrer

Wagner™ Jar – p/n 41170-00, 2-liter square plastic floc jar for the jar test. The Wagner Jar as a tap near the bottom of the jar to facilitate withdrawal of a sample for further testing of pH, turbidity, alkalinity, streaming current, zeta potential, etc.

The jar test is as much art as it is science. The idea is, one adds different coagulant doses to each of the 4 or 6 jars, permits a short period of rapid mixing (for coagulation) and then a longer period of slow mixing (flocculation) followed then by a no-stirring quiescent period to permit settling. Varying chemical doses for coagulants, pH adjustment, coagulant aids; ballasting substances (carbon, clay, etc.) also may be added to the jars.

During stirring and the quiescent period the operator or lab tech will observe the jar for floc formation and settling rate and use this information to then make chemical dose changes to the process. Each plant, operator and chemist (or University professor, engineer, chemical sales person, etc) is very jealous of their particular technique so one should tread carefully in suggesting any variation in their technique. Users will be adamant about use of a square vs. round jar, big jar or little jar, this rapid mix period vs. another, the slow stir speed, etc. They will be absolutely sure their combination of art and science is THE way to do it.

The jar test is an attempt to simulate in a one or two liter jar what is going on in a basin 20'X30'X15' containing 67,000 gallons. The jar test is an attempt to simulate with a little 1"x2" paddle stirrers and jars the mixing energy with a train of huge paddles extending the entire length of a 40 foot long flocculation chamber and maybe 15 feet in diameter.

It is as much an art as a science because operators have to learn to interpret "when my little jar looks this way, my big basin will look this way." The more measurements are made, the better the operator or lab person can interpretation the jar test –based more on measurement (science) and less dependant on art. This is important for filtration because how well the floc forms, settles and withstands shearing effects during mixing and filtration directly affects filter performance. Apparatus to enhance the jar test include a big array of other Hach products:

- HQd series or SensIon series pH meter and probe – One must measure pH especially with aluminum or iron salts (aluminum sulfate, liquid alum, ferric chloride, ferric sulfate). Coagulants have an optimal pH range for which they should be used. Aluminum sulfate or liquid alum work well from a pH of about 5.5 (optimum color removal) to the low 7's. Iron compounds – ferric sulfate and ferric chloride – operate well over a much wider range of pH well into the high 8's.
- Digital Titrator® and associated reagents to measure alkalinity – Use of the metallic salts as coagulants consumes alkalinity.
  - As a rule of thumb, one must have (numerically) ½ the alkalinity of the amount of coagulant dose needed. If a dose of 20 mg/l of alum is needed, then the alkalinity must be at least 10 mg/l.
  - Customers should be encouraged to monitor the alkalinity titration with pH measurement rather than trying to observe the color changes. Whether using methyl orange or bromcresol green/methyl red indicators, it is difficult for many if not most people to see the subtle color changes and thus to accurately determine the end point.
- Lab or portable turbidimeter (2100P, 2100N or 2100AN) – Use to measure the turbidity at the beginning, the turbidity of the supernatant at the end of the settling period and the turbidity after an aliquot of the supernatant after settling is passed through medium speed filter paper.
- Both a large (1-10ml) and small (0.1-1.0 ml) TenSette® Pipet – Use the TenSette to:
  - Prepare standard jar test solutions of the dry alum or iron coagulants.
    - If using 0.5 liter beakers, add 5 grams (5,000 mg) to one liter (1000 ml) of water for the stock solution. Then each 1ml contains 5 mg of the coagulant. So, each ml in a 0.5 liter jar results in 10 mg/l.
    - If using 1 liter beakers, add 10 grams (10,000 mg) to one liter (1000 ml) of water for the stock solution. Then each 1ml contains 10 mg of the coagulant. So, each ml in a 1 liter jar results in 10 mg/l.
    - If using 2 liter floc jars make the stock solution using 20 grams. Then again, each 1 ml of stock solution in 2 liters of sample results in 10 mg/l.

- Use to dose each of the jars with the appropriate coagulant/coagulant aid dose.
  - Use the 1-10 TenSette for 10 mg/l increments or
  - Use the 0.1-1.0 TenSette for 1 mg/l increments.
  - Realistically 1 mg/l increments are about all the resolution one can achieve with the jar test.
- Use to withdraw aliquot of supernatant
  - For testing turbidity and for a filtration test
  - Alkalinity measurement

- Plastic funnels and medium speed filter paper - filtering supernatant through medium speed filter paper is a surprisingly good simulation of what can be achieved with filtration in the plant's filters. Measure turbidity before filtration to determine effectiveness of settling and then after filtration to estimate how well the sample will hold up (floc tough enough to withstand the shearing forces) during filtration.

Figure 40: Six-place assembly for filtering samples after a jar test

- When a treatment plant uses liquid alum, or other liquid coagulant, coagulant aids or filter aids, the products can vary in percent of active component from manufacturer to manufacturer and in some cases from lot to lot. The percent concentration must be known before one can calculate how to make a standard solution (as above) for these liquid products.

Equipment and Apparatus for the Jar Test		
Cat. No.	**Description**	**Use**
Multiple Stirrer, choose one of the following		
26317-00	Phipps Bird 6-Place Programmable Multiple Stirrer supplied with 6 1-liter round glass beakers,	Multiple stirrer for jar test
27038-00	6-place nonprogrammable w/o beakers	Multiple stirrer for jar test
27040-00	4-place programmable w/o beakers	Multiple stirrer for jar test
27039-00	4-place nonprogrammable w/o beakers	Multiple stirrer for jar test
41170-00	Wagner Jar	2-liter square plastic floc jar
500-83	**Glass Beaker, round, 1 liter, pk/6**	Jar test w round jars
pH Meter, choose one of the following or better		
51700-11	**SensION 1 w/gel-filled combination pH**	Measure pH/ alkalinity end point
85059-00	**HQ11d pH meter w/ gel-filled combination pH electrode, buffers and probe stand**	Measure pH/ alkalinity end point
Digital Titrator, cartridges and indicators		
22709-00	**Universal Digital Titrator Kit w/ manual, 100 ml graduated cylinder, 125 and 250 ml Erlenmeyer flasks**	Alkalinity test
14388-01	**0.1600 N H_2SO_4 Titration Cartridge**	Low range alkalinity test
14389-01	**1.600 N H_2SO_4 Titration Cartridge**	High range alkalinity test
942-99	**Phenolphthalein PP, pk/100**	Indicator for p-alkalinity test
943-99	**Bromcresol Green Methyl Red PP pk/100**	Indicator for total alkalinity test
22719-00	**Reagent Set for Alkalinity – includes titration cartridges and indicators above.**	
Other Instruments and Apparatus		
46500-00 47000-00	**2100P Portable Turbidimeter OR** 2100N Laboratory Turbidimeter	Test clarity of supernatant and filtrate from jar test
19700-01	**TenSette Pipet, 0.1-1.0 in**	Jar test chemical dosing
21856-96	**Pipet tips, 0.1-1.0**	
19700-10	**TenSette Pipet, 1.0-10.0 in**	Jar test chemical dosing, transfer supernatant for further testing
21997-96	**Pipet tips, 1.0-10.0**	
1083-68	**Funnel, each**	Filtration testing of the supernatant
692-57	**Filters, pleated**	Filtration testing of the supernatant

Figure 41: Equipment and Apparatus for the Jar Test

4. Zeta Potential

Zeta potential is a test to quantify the charge on colloids in the water to be treated. Ideally one would like to be able to monitor the zeta potential of the raw water and thus with feed-forward control to set the coagulant dosage. In practice it is nearly universally used for feed-back control. That is, after coagulant addition a sample can be immediately taken to determine the charge neutralization. A zeta potential of zero is ideal. In practice most utilities will have a zeta potential after coagulation that is slightly negative. A positive zeta potential indicates a likely overfeed of coagulant. There are several drawbacks to use of zeta potential.

- It is a laboratory, grab sample tool.
- Instruments for measuring zeta potential are relatively expensive, typically on the order of $10,000.
- While they are not complicated tools, learning to interpret the data from a zeta meter is often time consuming.
    - There is not a clear cut procedure for how to interpret zeta potential measurements and apply them to the process. Every treatment plant is different, each water source is different.
    - Learning what zeta potential is ideal for a particular treatment plant and water involves repeated testing and observation. A good place to start is with the jar test. If a treatment plant has learned to interpret the jar test, then the zeta potential of the dosage selected during the jar test can be measured. And, a sample is also taken from the application point of the coagulant in the process immediately after rapid mixing. If the plant sample has a different zeta potential than the jar, the coagulant feed can be adjusted to match the zeta potential of the jar test.
    - After further observation of the process quality additional minor adjustments can be tried. Again the process observed and measured. The results are used to refine judgments made both in the process and in interpretation of the jar test.
    - This trial and error process carried out over time in a disciplined manner will result in a better optimized chemical feed. While a jar test may indicate a coagulant dose to the nearest 2-3 mg/l, using zeta potential can refine that judgment to within tenths of a mg/l of coagulant. The time invested is well spent as savings in several areas of the treatment process will result. Properly applied the return on investment can easily be less than a year.
- The bottom line is few utilities use measurement of zeta potential. Cost, complexity, lack of understanding of the principle and lack of the desire for disciplined study have limited the use of this very valuable tool.

5. Streaming Current

Steaming current is an on-line measurement of how well charge neutralization has occurred. It is not the same as zeta potential but can provide much the same level of information for process control. It has both drawbacks and advantages over zeta potential measurement.

- It is an on-line measurement providing continuous feedback
- Optimally, one would use both zeta potential and streaming current measurement.
- Streaming current is strongly influenced by salinity, conductivity and pH variations. If the pH, conductivity or salinity of the water to be treated is highly variable streaming current measurements may have limited value or will be problematic.
- Streaming current requires much less effort to learn to use than a zeta potential measurement.
- Streaming current meters are less expensive than zeta meters.
- One of the greatest challenges of streaming current application is locating the right point of measurement. The sample must be as close as possible to the point of application of the coagulant but after it is well mixed. Often the ideal point is not accessible.

6. Microscopic Particulate Analysis

"The Microscopic Particulate Analysis (MPA) involves the identification, sizing and population estimates of microorganisms and organic or inorganic debris found in water. Samples for MPA are collected by passing water through a cartridge filter with a nominal pore size of one micrometer (μm). In the laboratory, particles trapped on the cartridge filter are washed from the filter, concentrated to a small volume, and observed at 100 to 1,000 magnifications using light microscopy. Comparing the particles in a filtration plant's raw water and filtered water provides one tool in assessing the effectiveness of treatment and the ability to remove *Giardia*-sized and *Cryptosporidium*-sized material. The method is also used to detect surface water microorganisms in a suspect groundwater source or infiltration gallery." (Ref 1)

MPAs require the skills of a very experienced microscopist. While a few utilities have a person on staff with sufficient training in microbiology and use of the microscopes and experience in particulate identification, most do not. And an MPA is required so infrequently that most utilities find it's best to send samples to a consulting laboratory periodically.

7. Turbidity Measurement

Turbidity measurement of granular media filters is a regulatory requirement in the United States and many other countries. Typically a continuous turbidity measurement is required on every individual filter effluent plus on the combined filter effluent. Turbidity measurement in its simplest application is an aesthetic measurement of clarity. Turbidity monitoring requirements are however ubiquitous in drinking water regulations reflecting much greater importance than a simple clarity measurement. Notice in the following table the use of turbidity measurement for establishing treatment credits as an example of the broad importance of turbidity measurement

TABLE IV.D–1.—MICROBIAL TOOLBOX: OPTIONS, CREDITS AND CRITERIA

Toolbox option	Cryptosporidium treatment credit with design and operational criteria [1]
Source Protection and Management Toolbox Options	
Watershed control program	0.5-log credit for State-approved program comprising required elements, annual program status report to State, and regular watershed survey. Unfiltered PWSs are not eligible for credit.
Alternative source/intake management.	No prescribed credit. PWSs may conduct simultaneous monitoring for treatment bin classification at alternative intake locations or under alternative intake management strategies.
Prefiltration Toolbox Options	
Presedimentation basin with coagulation.	0.5-log credit during any month that presedimentation basins achieve a monthly mean reduction of 0.5-log or greater in turbidity or alternative State-approved performance criteria. To be eligible, basins must be operated continuously with coagulant addition and all plant flow must pass through basins.
Two-stage lime softening	0.5-log credit for two-stage softening where chemical addition and hardness precipitation occur in both stages. All plant flow must pass through both stages. Single-stage softening is credited as equivalent to conventional treatment.
Bank filtration	0.5-log credit for 25-foot setback; 1.0-log credit for 50-foot setback; horizontal and vertical wells only; aquifer must be unconsolidated sand containing at least 10 percent fines (as defined in rule); average turbidity in wells must be less than 1 NTU. PWSs using existing wells followed by filtration must monitor the well effluent to determine bin classification and are not eligible for additional credit.

TABLE IV.D–1.—MICROBIAL TOOLBOX: OPTIONS, CREDITS AND CRITERIA—Continued

Toolbox option	Cryptosporidium treatment credit with design and operational criteria [1]
Treatment Performance Toolbox Options	
Combined filter performance	0.5-log credit for combined filter effluent turbidity less than or equal to 0.15 NTU in at least 95 percent of measurements each month.
Individual filter performance	0.5-log credit (in addition to 0.5-log combined filter performance credit) if individual filter effluent turbidity is less than or equal to 0.15 NTU in at least 95 percent of samples each month in each filter and is never greater than 0.3 NTU in two consecutive measurements in any filter.
Demonstration of performance	Credit awarded to unit process or treatment train based on a demonstration to the State with a State-approved protocol.
Additional Filtration Toolbox Options	
Bag and cartridge filters	Up to 2-log credit with demonstration of at least 1-log greater removal in a challenge test when used singly. Up to 2.5-log credit with demonstration of at least 0.5-log greater removal in a challenge test when used in series.
Membrane filtration	Log credit equivalent to removal efficiency demonstrated in challenge test for device if supported by direct integrity testing.
Second stage filtration	0.5-log credit for second separate granular media filtration stage if treatment train includes coagulation prior to first filter.
Slow sand filters	2.5-log credit as a secondary filtration step; 3.0-log credit as a primary filtration process. No prior chlorination.
Inactivation Toolbox Options	
Chlorine dioxide	Log credit based on measured CT in relation to CT table.
Ozone	Log credit based on measured CT in relation to CT table.
UV	Log credit based on validated UV dose in relation to UV dose table; reactor validation testing required to establish UV dose and associated operating conditions.

[1] Table provides summary information only; refer to following preamble and regulatory language for detailed requirements.

Figure 42: EPA Toolbox Options, Credits and Criteria

The figure below summarizes turbidity measurement requirements. Monitoring requirements vary depending on which rule applies to the system: Surface Water Treatment Rule (SWTR), the Interim Enhanced Surface Water Treatment Rule (IESWTR) or the Long-Term 1 Enhanced Surface Water Treatment Rule (LT1SWTR or often just LT1). And notice:

1. State primacy agencies are always given additional latitude to make more stringent rules.
2. States may in some cases to make less stringent rules (as in monitoring frequency for small systems).
3. Due to the complexity of the rule, it is best to let the individual water system work directly with the relevant primacy agency to determine which set or sets of rules apply to them.
4. It is incumbent on the individual RSM to become familiar with the rules in the particular State or States within the sales territory. The variety of rules and requirements for all the states cannot be summarized in this document.
    a. Don't get between the customer and the regulatory individual or agency.
    b. Let the state make the rule, let the customer find out from the state how the rule applies to them.
    c. Consult with the customer and perhaps the state to see which instrument best will address the needs of the customer and meet regulatory requirements. For instance you may want to help the customer speak with the state about substituting a FilterTrak 660 when a particle counter is specified on a membrane system.

<table>
<tr><th colspan="6">Turbidity: Monitoring and Reporting Requirements</th></tr>
<tr><td colspan="6">Two ways of turbidity measurement: Combined Filter Effluent (CFE) and Individual Filter Effluent (IFE)</td></tr>
<tr><td colspan="2">Reporting Requirements – due 10th day of the following month</td><td>Monitoring/ Recording Frequency</td><td>SWTR as of June 29, 1993</td><td>IESWTR ≥ 10,000 people as of January 1, 2002</td><td>LT1ESWTR < 10,000 people as of January 1, 2005</td></tr>
<tr><td colspan="6">Conventional and Direct Filtration</td></tr>
<tr><td colspan="2">CFE 95% Value
Report total number of CFE measurements and number and percentage of CFE ≤ 95% confidence limit</td><td>At least every 4 hours*</td><td>≤ 0.5 NTU</td><td>≤ 0.3 NTU</td><td>≤ 0.3 NTU</td></tr>
<tr><td colspan="2">CFE Maximum value. Report date and value of any CFE measurement that exceeded CFE maximum</td><td>At least every 4 hours*</td><td>5 NTU Contact State within 24 hours</td><td>1 NTU Contact State within 24 hours</td><td>1 NTU Contact State within 24 hours</td></tr>
<tr><td colspan="2">IFE Monitoring. Report IFE monitoring conducted and any follow up actions</td><td>Continuously at least every 15 minutes</td><td>None</td><td>Monitor-exceedances require follow-up action</td><td>Monitor-exceedances require follow-up action**</td></tr>
<tr><td colspan="6">*State may reduce frequency to once per day for systems serving ≤ 500
**Systems with two or fewer filters may monitor only CFE continuously in lieu of IFE</td></tr>
<tr><td colspan="6">Slow Sand, Diatomaceous Earth and Alternative Technologies</td></tr>
<tr><td rowspan="2">Slow Sand and Diatomaceous Earth</td><td>CFE 95%</td><td>At least every 4 hr*</td><td>≤ 1 NTU</td><td colspan="2">Regulated under the SWTR</td></tr>
<tr><td>CFE Max</td><td>At least every 4 hr*</td><td>5 NTU</td><td colspan="2">Regulated under the SWTR</td></tr>
<tr><td rowspan="2">Alternative Technologies
Membranes
Cartridges
Other</td><td>CFE 95%</td><td>At least every 4 hr*</td><td>≤ 1 NTU</td><td rowspan="2">Established by State</td><td>Established by State (not to exceed 1 NTU)</td></tr>
<tr><td>CFE Max</td><td>At least every 4 hr*</td><td>5 NTU</td><td>Established by State (not to exceed 5 NTU)</td></tr>
<tr><td colspan="6">Monitoring frequency may be reduced by the State to once per day for systems using slow sand or alternate filtration. Monitoring frequency may be reduced by the state to once per day for systems serving < 500 or fewer people regardless of type of filtration used.</td></tr>
</table>

Figure 43: USEPA Turbidity Monitoring Requirements

But wait, that's not all. If there is an exceedance of the individual filter rules, there is follow up as illustrated below.

IFE Follow-Up and Reporting Requirements						
	IESWTR (≥ 10,000)			LT1ESWTR (< 10,000) **		
Condition	Action	Report	By	Action	Report	By
2 consecutive recordings >0.5 NTU taken 15 minutes apart at the end of the first 4 hours of continuous filter operation after backwash/offline:	Produce filter profile within 7 days (if cause not known)	▸ Filter # ▸ Turbidity value ▸ Date ▸ Cause (if known) or report profile was produced	10th of the following month			
2 consecutive recordings > 1.0 NTU taken 15 minutes apart:	Produce filter profile within 7 days (if cause not known)	▸ Filter # ▸ Turbidity value ▸ Date ▸ Cause (if known) or report profile was produced	10th of the following month		▸ Filter # ▸ Turbidity value ▸ Date ▸ Cause (if known)	10th of the following month
2 consecutive recordings > 1.0 NTU taken 15 minutes apart at the same filter for **3 months in a row**:	Conduct filter self-assessment within 14 days	▸ Filter # ▸ Turbidity value ▸ Date ▸ Report filter self-assessment produced	10th of the following month	Conduct a filter self-assessment within 14 days. Systems with 2 filters that monitor CFE in lieu of IFE must do both filters.	▸ Date filter self-assessment triggered & completed	10th of the following month (or within 14 days of filter self-assessment being triggered if triggered in last 4 days of the month)
2 consecutive recordings > 2.0 NTU taken 15 minutes apart at the same filter for 2 months in a row:	Arrange for CPE within 30 days & submit report within 90 days	▸ Filter # ▸ Turbidity value ▸ Date	10th of the following month	Arrange for CPE within 60 days & submit CPE report within 120 days	▸ Date CPE triggered	10th of the following month
		Submit CPE report	90 days after exceedance		Submit CPE report	120 days after exceedance

** Systems serving fewer than 10,000 people must begin complying with these requirements beginning January 1, 2005.

Figure 44: IFE Follow up and reporting requirements

Process Turbidimeters and Their Applications for Water Treatment Monitoring			
Instrument	Regulatory Compliance	Range	Best Application
1720E	US EPA 180.1	0-100 NTU	Filter Effluent
FT 660	US EPA Approved Hach Method 10133	0-5000 mNTU	Filter Effluent, Membrane Permeate
Ultra Turb	ISO 7027 Not US EPA reportable	0-1000 NTU	Filter Influent and Effluent
Solitax	ISO 7027 Not US EPA reportable	0-1000 NTU or up to 150 g/l solids	Raw water and filter influent; Monitoring backwash and backwash recycle
Surface Scatter 7	US EPA 180.1	0-10,000 NTU	Raw water and filter influent; backwash recycle

Figure 45: Hach turbidimeters for filtration monitoring

8. Particle Counting

In the United States particle counters were first used continuously beginning in about 1975 by the Southern Nevada (Las Vegas) water treatment plant which uses Lake Mead as its source of water. The Central Utah Water Conservancy District (Orem, Utah) started using particle counters a couple of years later. Particle counters used by the water industry in these early applications were instruments designed for monitoring hydraulic fluids or ultrapure water in semiconductor or pharmaceutical applications. Neither design is very good for drinking water as they were expensive and difficult to maintain. So few utilities were interested in particle counting that particle counter manufacturers could not invest in designing a particle counter optimized for using in drinking water.

Particle counting for municipal water did not become common until the 1990's and came as a result of an outbreak of cryptosporidiosis at Carrolton, GA. The State of Georgia began requiring every filter to have a particle counter. Georgia is still the only primacy agency in the United States that mandates particle counting on conventional filtration. This finally served as the catalyst to get particle counter manufacturers interested in designing a instrument meant specifically for the water industry.

In the early 1990's Hach Company became interested and partnered with Hiac Royco (now part of Hach Ultra Analytics) to offer a portable instrument, the Log Easy - an excellent tool. But the Log Easy was a modification of a portable particle counter originally intended for air monitoring and really not optimized for water treatment applications and it was expensive. From about 1995 to 2000, Hach Company partnered with PMS to offer the Hach 1900 WPC (water particle counter). The 1900 WPC was constructed from an *in situ* sensor design – again originally intended for other applications. The sensor in the 2200 PCX (essentially identical to the Met One PCX) is the first particle counter sensor designed specifically for the water industry. The sensor, the DWS (Drinking Water Sensor) is a volumetric, light-blocking sensor with sensitivity to 2µm.

Hach also sells the PCT and the WGS 267 portable particle counter both of which are labeled as a Met One. All contain the DWS sensor and thus have the same concentration limit (17,000 particles/ml >2µm), sensitivity (2µm) and resolution (better than 10% at 10 µm, typically better than 5%)

Hach Company's Particle Counter Offerings for Drinking Water			
All products are manufactured by Hach Company			
Specification	Hach 2200 PCX	Met One PCT	Met One WGS 267
Application	**Continuous, On-line**	**Continuous, On-line**	**Grab sample, portable**
User bin sizes, channels	**32 user-selectable**	**2, factory set to user's requirements**	**6, factory set**
Enclosure	**NEMA 4X fiberglass**	**NEMA 4X fiberglass**	**Gasketed steel**
On-board memory	**N/A**	**N/A**	**250 measurement buffer**
Mode	**Cumulative and/or Differential**	**Cumulative**	**Cumulative and/or Differential**
Local display	**LED**	**LED**	**LED**
Built-in printer	**N/A**	**N/A**	**Thermal printer**
Communication			
Digital	**RS485**	**RS485**	**RS232**
Analog	**Optional 8 analog in/8 analog out, fully user configurable**	**2 Analog out**	**N/A**

Figure 46: Hach particle counters

There was and in some quarters still is an interest in mandating a particular particle number in drinking water. Many utilities operate at less than 5 particles/ml >2µm while others that also are well operated may be in the hundreds. One utility has particle counts consistently greater than 300 particles/ml >2µm. The cause is very hard water and the particles are suspended calcium. The inability to set a uniform particle limits for all water plants will likely inhibit particle counting from ever becoming a universally mandated measurement as is turbidity. In the United States, only the State of Georgia requires particle counting.

Regulatory agencies do however sometimes mandate use of a particle counter for particular situations such as for membranes; for plants wanting to implement as yet unproven treatment techniques; or, for treatment plants who want to operate filters at a high rate. For example when the now accepted AccuFloc system of ballasted flocculation was introduced it was common for regulatory agencies to require use of particle counting in the engineering pilot study evaluations and sometimes in the full scale treatment plant.

It is most valuable to monitor particle counts on both filter influent (clarifier effluent) and filter effluent to compare particle removal and to express the removal as log removal. Monitoring raw water with a particle counter may not be practical. The concentration limit, as shown in the table is 17,000 particles/ml >2µm. That limit will typically be exceeded at about 5 NTU. However in some cases the limit can be exceeded at as little as 1 NTU and in other waters still be within range as high as 10 NTU. In addition, monitoring raw water may require frequent sensor cleaning – as often as once a week and in some cases several times per day. But where conditions permit, monitoring raw water particle counts is useful.

In addition to each individual filter one should also consider combined filter effluent and clearwell effluent. It is reasonable to ask, “why the clearwell, isn’t it the same as the combined filter effluent?” No, they are not necessarily the same. Differences can occur due to addition of other treatment chemicals for: pH adjustment, corrosion control chemicals (phosphates), fluoride. And a structural failure or intrusion of ground water can be detected.

Log Removal

As can be seen in Figure 42, EPA Toolbox Options, Credits and Criteria, the terms ‘log removal’ or log credit are widely used to express performance of various treatment processes. The terms can be somewhat confusing for users. Recall a logarithm is the exponent to which a number is raised for a particular number base, in the 10-base counting system it is the exponent to which 10 is raised. The log removal calculation is straight forward: log(Influent/effluent) which can also be calculated as log(influent) – log(effluent). (Recall from algebra, log (a/b) = log a – log b)

For example, if a raw water has 16,000 particles/ml >2µm

- 16,000 = 1.6 X 10^4, or log 16,000 = 4.204, or 16,000 = $10^{4.204}$
- If after filtration the water has 16 particles/ml >2µm,
    - then there was a 3 log removal (10^3) –the decimal moved to the left 3 places.
    - Or, 99.9 % of the particles (16,000-16/16,000 = 0.999 or 99.9%)
- If the effluent counts were 123, then the log removal would be log(16,000/123) or log(16,000) – log(123) = 2.114.

Percent Removal	Decimal equivalent	Log Removal
90 %	0.90	1 log
99 %	0.99	2 log
99.9 %	0.999	3 log
99.99 %	0.9999	4 log

Figure 47: Percent vs. Log Removal

For some treatment processes, it is problematic to express results in terms of log removal. When monitoring membranes with a particle counter, permeate (effluent) may approach zero particle counts. As the permeate approaches zero particle counts log(influent/effluent) becomes undefined – division by zero. Rearranging the expression to log(influent) – log(effluent) does not solve the problem. There is no exponent (logarithm) to which any number can be raised which will yield zero. Log(0) is undefined. Hence if the effluent approaches zero, it is best to express the removal as a percent removal. For these reasons, the WQS Vista software for the particle counters provides the user the option to express removal as a logarithm or a percent.

It makes sense to express quantitative measurements (particle counts, number of cysts or oocysts, mg/l of iron) in terms of log reduction or log removal. It does not make sense to express qualitative measurements, like turbidity, in terms of log removal. In spite of this, users and even some regulatory personnel and agencies will use ‘log removal of turbidity’ as a criteria for performance.

“Turbidity is not a direct measure of suspended particles in water but, instead, a measure of the scattering effect such particles have on light." (Reference: Turbidity Science, Hach Company, M Sadar. Original edition titled: Understanding Turbidity Measurement, Hach Company, Clifford Hach).

One certainly can express any number of measurements in terms of log removal or percent removal if it makes sense to the user to do so. It doesn't make any sense but one could maintain that starting at a pH of 14 and ending at a pH of 1.4 is a "one log removal." (You could have done this with the Vista software and this is the result).   Actually pH is a logarithmic function. A change from pH 14 to 13 is a one log change. Is that one log removal?   Here lies the crux of the problem of encouraging customers to think of turbidity in terms of log removal. **Sooner or later someone will ask you to prove it.**

So the raw turbidity is 2.5. And so the 1720E reads 0.028 on filter effluent - that's less than 2-log removal. Shazam!! With the FT660 I can read 0.023 so now I can say I have 2+ log removal?! No one on the face of the earth can prove there is any difference between 0.023 and 0.028 NTU. For that matter, we can't prove there is any difference between 0.02 and 0.05! You can't prove it within instrument makes/models and you sure can't prove it between different makes/models.

If you promote use of turbidity measurement to express a log removal, you will put yourself in the indefensible position eventually of having to prove the difference between 0.023 and 0.028. The customer will demand you show it it's really 2 log removal at 0.023 instead of less than 2 log a 0.028.

IT'S THE TREND THAT IS IMPORTANT, NOT THE NUMBER. It's all about process control. It's about seeing variation, learning the cause of variation and correcting it! At the very low turbidity levels, the FT 660 is better able to see process variation than the 1720E and therefore for utilities desiring to optimize process control, the FT660 is a better choice.

If a customer thinks it is meaningful to express turbidity in terms of log removal, that's their business. If some State agency wants to condone it, that's their business. But you should not encourage it or condone it because, YOU CAN'T PROVE IT AND NEITHER CAN THEY! If they ask your opinion of the validity of the practice answer truthfully that you don't believe the approach has merit and then will explain why - as above.

Turbidity and Particle Counting are Complementary Technologies

Turbidity and particle counting are the primary measurements for evaluating performance of granular media filtration systems. Turbidity measurement and particle counting measurement are complementary technologies. One does not replace nor compete with the other.   Understanding how the two technologies are complementary will be invaluable in using the two technologies to understand filtration measurement.

Turbidity Measurement	Particle Count Measurement
Measurement of light scattered at an angle. For municipal water/wastewater applications light scattering measurements at 90º to the incident light path.	Particle counting measurements can be light scattering or light blocking. Light scattering technology is appropriate for particle sizes <1µm. Light blocking technology is appropriate for particle sizes $\geq$ 1µm. For municipal drinking water applications, light blocking $\geq$ 1µm (typically >2µm) is appropriate.
Not a specific measurement of anything, it is a qualitative measurement	A quantitative measurement of particle size and particle number.
Measurement is independent of volume	Measurement is volume dependent
Measurement is relatively independent of flow rate. Sample can be flowing or static	Sample must be flowing and flowing at a constant rate.
Unit of measurement is nephelometric turbidity units, NTU	Unit of measurement is particle counting must state the number of particles, particle size or range of sizes and unit volume. For example 10 particles per ml > 5µm or 200 particles per ml 2-5µm.
Peak wavelength response for lab, SS7 and 1720 series process is ~560nm, FT660 is 660 nm, for Accu4 ~ 850nm	Wavelength is 790 nm
Theoretical particle size sensitivity 10^{-8}m (0.01µm)	2200 PCX sensitivity is $\geq$ 2µm
Size range from approximately 10^{-8}m - 10^{-3}m (large molecules to sand)	For the 2200 PCX: 2-750 µm
Color in water is a negative interference except for the Accu 4	Color does not interfere with particle count measurements
Turbidity interferes. High turbidity is a negative interference. At high turbidity scattered light is blocked or absorbed by the large amount of turbidity and thus does not reach the detector. The turbidity will be false negative. This phenomenon is called 'going blind.'	Turbidity interferes. High turbidity is a negative interference. Particle counters typically have a range of approximately 17,000 particles/ml > 2µm. The particle counter may be over range at turbidity between 1 and 10 NTU – typically approximately 5 NTU. The particle counts will be false negative. This phenomenon is called 'going blind.' A particle counter is basically a clean water tool.
Light absorbing materials (i.e. activated carbon) are negative interferences.	Light absorbing materials (i.e. carbon) block light well and thus are counted. They do not interfere
Accuracy of measurement is influenced by particle size	Accuracy of measurement is influenced by particle size
Accuracy of measurement is influenced by particle shape	Accuracy of measurement is influenced by particle shape
Accuracy of measurement is influenced by a particle's refractive index	Accuracy of measurement is influenced by particle's refractive index

Figure 48: Comparison of particle counter and turbidimeter characteristics

To illustrate how the measurements are complementary, consider the following chart:

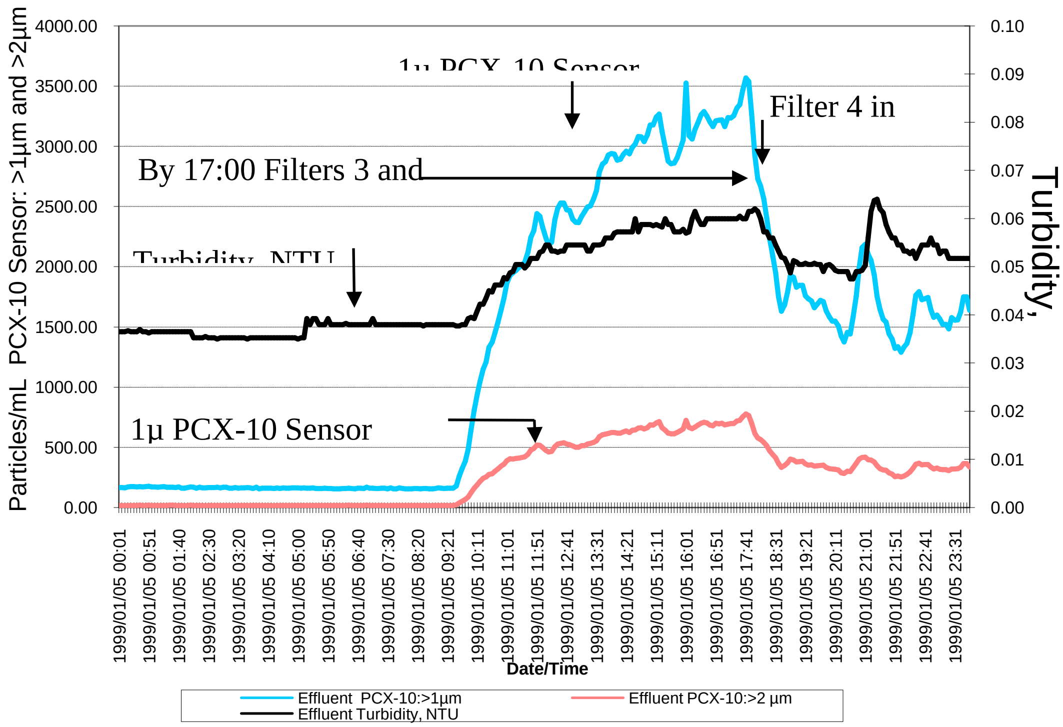

Figure 49: Response of Particle Counter and turbidimeter to fluoride and carbon

The chart illustrates two channels of data from a single particle counter with 1µm sensitivity set with channels for >1µm and >2µm and a process turbidimeter (Hach Company 1720C). Looking at this figure, at about 9 AM, particle counting and turbidity measurements showed deviation. The particle counts jumped over a decade (>1µm from approximately 180 particle/ml to about 3500 particles/ml; >2 µm from 20 particles/ml to about 600) while the turbidity measurement barely moved – from 0.04 to 0.06 NTU. As a matter of fact, without comparison to the particle count measurements one could contend the variation in turbidity measurement was insignificant. Once again though, comparing the shapes of the particle counter and turbidimeter curves it is evident both the particle counter and the turbidimeter responded to the same event.

Why did the particle count measurement jump so sharply and the turbidity measurement barely move? Understanding each measurement was essential to understanding the cause. In this case sodium silicofluoride that was out of spec in particle size and also contaminated with carbon was added to a chemical feeder. The contaminated fluoride hit the water at about 9:21 am. The particle counter responded very strongly because the particle counter responded to both the fluoride particles and the carbon particles. The turbidimeter (a 1720C) responded positively to the fluoride particles but carbon particles were a negative interference. Thus, the two instruments show nearly an identical response curve yet the magnitude of the change is much greater in the particle count measurements than in the turbidity measurements due to the negative error in turbidity measurement caused by the carbon. **Particle counting and turbidity measurements are complementary not competing technologies!**

Using the two instruments together and understanding the similarities and differences in the measurements provided the answer to the cause of the excursion. Learning how to properly use and interpret data from particle counters and turbidimeters is essential to successfully using these two valuable tools together to achieve process control and process optimization.

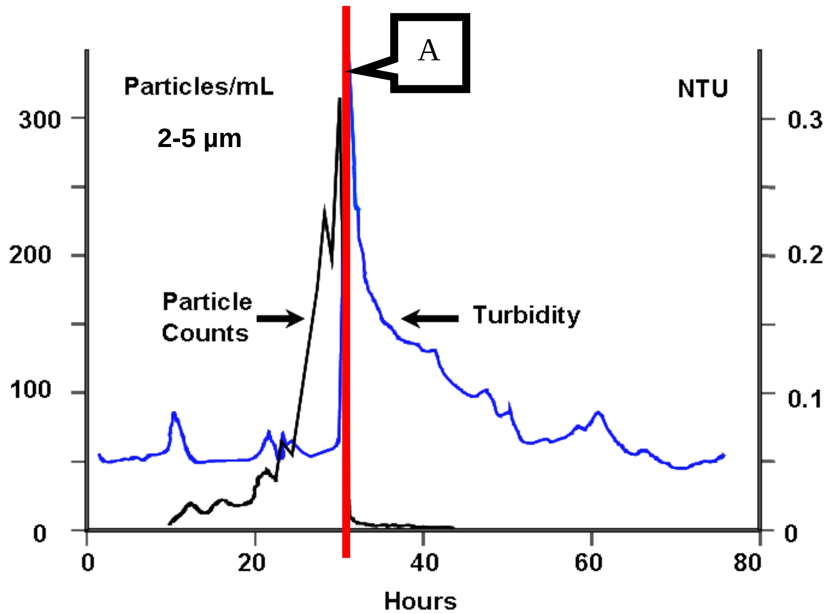

Figure 50: Time relationship of particle counter and turbidimeter

Consider the illustration above. These are actual data. Data don't lie but… with a little slight of hand…

This illustration or one similar was used by most particle counting proponents to illustrate 'particle counters respond hours sooner than turbidimeters. The red line (A) is the peak of the backwash curve. To the left the particle counter salesman says, *"See the particle counts started to increase at about 15 hours and increase sharply at about 25 hours. The turbidity didn't respond until nearly backwash, at 30 hours. So particle counts responded at least 4-5 hours sooner."* Really?

Look back to about 10 hours. For each tick up in particle counts there is a tic up in turbidity measurement. The amplitude is different, granted. But the turbidimeter was responding. Both instruments told of the impending upset. Look now to the right side of the red line.

On this side of the red line are the end of backwash and the filter being put back on line. The particle counters salesman says, *"Look, the particle counts come down faster so there is less filter to waste. Notice the turbidity doesn't return to normal for almost 20 hours. Get back on line hours sooner with a particle counter."* Really?

The particle counts are 2-5 microns. After backwash it is the smaller particle sizes screaming though the filter! Remember, nephelometers (turbidimeters) are sensitive to particles almost 2 decades smaller that the sensitivity of drinking water particle counters! On the right, the turbidimeter is seeing the cloud of small particles the particle counter cannot see! Thus the right approach is to say, "Hey, what can we do to the way the filter is operated or the coagulant feed or to the way a filter aid is added to get the turbidity to come down at the same rate as the particle counts?"

Particle counting and turbidity measurement are complementary, not competing technologies. More can be learned by using them together. One does not replace the other.

Instruments don't just provide a measurement to be recorded and then forever ignored. Instruments ask questions; questions about the process! Learning to interpret instrumental measurements in the view of "what question is the instrument asking" is the key to successful use of the instrument as a process control tool. One way to learn what question is being asked is to look at different measurements, i.e. turbidity vs. particle counting, pH vs. particle counting, turbidity vs. headloss, etc. Helping customers learn to view instrumental measurements as process control questions will enhance the stature of the sales person to the customer and lead directly to increased use of (hence purchase of) the instruments as well as loyalty to the sales person.

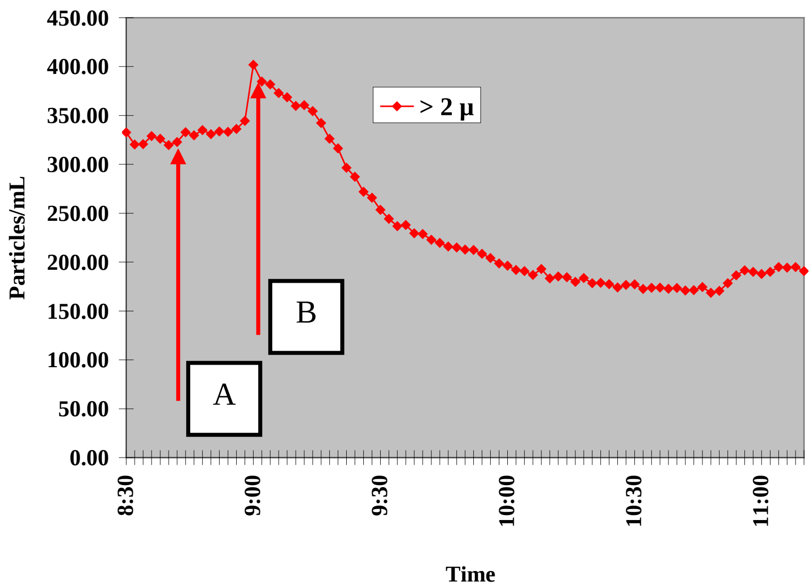

Figure 51: Particle count vs. pH change

Figure 51 illustrates particle counts changing in time with an abrupt change at 9 AM. That's a question! What caused this change was a change in pH. Alum was being used as a coagulant prior to filtration. The pH during coagulation was about 7.8. A pH of 7.8 (A) is too high for optimal use of alum. At 9 AM (B) a sulfuric acid feed was started which dropped the pH to 7.2. While still not ideal, 7.2 is a much better pH for alum coagulation than is 7.8. Instruments ask questions. To the extent an operations staff is able to learn to interpret instrumental measurements as questions, they will gain better control of the process.

Turbidity and Particle Counts as Surrogates for Protozoan Cysts and Oocysts

Protozoan cysts and oocysts such as *Giardia lamblia* (causes Giardiasis) and *Cryptosporidium parvum* (causes Cryptosporidiosis) require expert microscopic examination to identify their presence and it is not practical to monitor with great enough frequency. A surrogate has been sought for these organisms that are easier to identify and monitor. The vision has been to find something that would serve the same purpose as the coliform group has served for monitoring bacteria in water – simply an indicator the problem organisms might exist. A number of microorganisms and even plant spores have been tried but none has been yet identified. But, it has consistently been demonstrated that low particle counts and low turbidity correspond to an absence of protozoan cysts and oocysts. That is the basis for the current requirement the turbidity should be less than 0.3 NTU. The correlation to absence of cysts and oocysts is especially good below 0.1 NTU.

TABLE IV–15.—STUDIES OF *Cryptosporidium* REMOVAL AT DIFFERENT EFFLUENT TURBIDITY LEVELS

Microorganism	Average of log removals	Filtered effluent turbidity	Experiment design	Researcher
Cryptosporidium	4.39	≤0.1 NTU	Pilot-scale	Patania et al. (1995).
	3.55	>0.1 and ≤0.2 NTU		
Giardia	4.23	≤0.1 NTU		
	3.22	>0.1 and ≤0.2 NTU		
Cryptosporidium	4.09	≤0.1 NTU	Bench-scale	Emelko et al. (1999).
	3.58	>0.1 and ≤0.2 NTU		
Cryptosporidium	3.76	≤0.1 NTU	Pilot-scale	Dugan et al. (2001).
	2.56	>0.1 and ≤0.2 NTU		

Federal Register, Vol. 68, No. 157, Monday Aug 11, 2003, pg 47698

Figure 52: Relationship of turbidity to absence of protozoan cysts and oocysts

According to Hendricks (Ref 22):

> Effluent turbidity and effluent particles were considered the most practical of the surrogates explored. They approached being the "ideal" surrogates. Measurements had high precision (low standard deviation) high reliability and low labor requirements (considering maintenance) and showed a well defined relationship with the logR (pathogen) distributions.

Summary

If we can measure that of which we speak and express it in number, we know something of our subject. If we cannot measure and express it as a number our knowledge is meager and unsatisfactory. Lord Kelvin.

The sentiment expressed by Kelvin is what has provided a market for Hach Company's products. Process control and quality improvement - whether in manufacture of analytical instruments, treatment of potable or industrial waters and wastewaters, manufacture of rockets and widgets – depend on accurate, reliable measurement. At Hach, maintaining and improving the quality of the product requires identifying and eliminating variation in the manufacturing process. So too with water treatment. Variations in the process must be identified and eliminated to maintain and improve the treatment process.

Not much has changed in water treatment in the last 4000 years. Many of the processes used today were described in literature dating to 2000 BC. One of the keystones of modern water treatment, the concept of the multiple barrier has also been described and used for centuries. Water treatment will to some extent always rely on the skill of the operations staff – the art of water treatment. Much of what was art is now science. As Hudson pointed out, "More than to any other development, credit for improvement of water quality is due to the development of reliable water quality monitoring devices in the last two decades."

Modern filtration practices are a result of a better understanding of the mechanisms of filtration. But the existence of filtration is no guarantee of safe water as was observed in Germany in 1893: "The bed must be complete in every particular and the filtration must be conducted in the most thorough and painstaking manner with the frequent bacteriological examinations for the control of the filter. Epidemics of typhoid fever in Altona have demonstrated the existence of a connection between the disease and imperfect filtration." *Without measurement, our knowledge is meager and unsatisfactory.*

The quality of water applied to a filter (filter influent) will directly affect how well a filter performs. Measurement of the processes leading up to filtration – sedimentation, coagulation, and flocculation – is important if the filter is to function properly and provide quality effluent at a reasonable cost.

The granular media filter is an expensive, complex piece of equipment that must be properly cared for if it is to function properly. Measurement is important in every aspect of filtration to ensure water quality is maintained but also to manage the filter during filtration and during filter cleaning.

The bottom line: The water treatment process in general and the filtration process in particular depends on accurate, reliable measurements to ensure safe water and also to produce water of the highest aesthetic quality while controlling treatment costs.

Hach's role is to

- Provide instruments with sufficient sensitivity and accuracy to permit continued identification of process variation.
- Assist the customer in getting optimal use of the measurement tool by
  - Selecting the right tool,
  - Suggesting the best installation,
  - Assisting with understanding instrument function.
- Demonstrate how a variety of measurement are
  - Complementary
  - Helpful in identifying and correcting operational anomalies, and
- Teach the customers that instruments don't simply provide measurements. Instruments ask questions about the process. Answering those questions will lead to further process improvement.

Acknowledgement

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