

Filtration in the Use of Individual Water Purification Devices



Technical Information Paper # 31-004-0211

PURPOSE

This information paper provides an in-depth review of filtration (including adsorption and ion exchange) as a pathogen and particulate reduction mechanism when treating natural waters. This paper is intended to assist the reader in evaluating the capabilities of Individual Water Purification Devices (IWPDs) using size exclusion, adsorption, and/or ion exchange to reduce disease-causing bacteria, virus, and protozoan cyst populations, as well as turbidity causing particulate matter.

REFERENCES

Appendix A contains a list of references.

INTRODUCTION

Background

Understanding the ability of filtration to reduce disease-causing microorganisms is important in protecting Soldiers, who are considering using this technology, from acute health threats posed by these microorganisms. Soldiers deployed beyond traditional field drinking water supplies must have access to potable water. Using IWPDs is one way to provide microbiologically safe water in these situations. These IWPDs must protect the Soldier from acute microbial health threats. The U.S. Environmental Protection Agency (USEPA) Guide Standard and Protocol for Testing Microbiological Water Purifiers (reference 1) provides performance standards by which an IWPD using filtration can be evaluated. The performance standards are a minimum 6-log reduction/inactivation of bacteria, 4-log reduction/inactivation of viruses, and 3-log reduction/inactivation of protozoan cysts (typically *Giardia* or *Cryptosporidium*). Any IWPDs meeting these standards are considered effective at reducing disease causing bacteria, viruses, and protozoan cysts. Some IWPD manufacturers test their devices using this protocol. This is considered the best way to evaluate the IWPDs pathogen reduction capabilities. In the absence of that testing data, this information paper can be used to gain an understanding of the advantages as well as limitations of filtration and help determine if an IWPD using filtration could successfully meet the USEPA Guide's minimum performance standards.

Origin of Filtration for Water Treatment

For the purpose of this paper, filtration will be used broadly to incorporate separation by (1) granular media, (2) size exclusion (e.g., membranes), (3) electrochemical adsorption (e.g., activated carbon), and (4) ion exchange (e.g., anion, cation exchange). Filtration is a well studied process for drinking water treatment. Naturally, as groundwater migrates in the subsurface, contaminants are removed from the water due to ionic attraction as well as sieving based on size. Concurrently, contaminants such as iron and manganese may be dissolved into the groundwater

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and often remain in the dissolved form until pumped to the surface. Similarly, microorganisms are imparted to and extracted from the groundwater during subsurface movement. Surface water (e.g., ponds, lakes, rivers), like groundwater, has ever-changing quality with respect to microorganisms, particulates, chemistry, etc., but is more exposed to human activity, oftendegrading water quality. To reduce water contaminants and create potable water safe for human consumption, water treatment has included filtration to mimic and better the natural removal of water contaminants. Filtration for water treatment dates back to 2000 b.c.e., where crude sand and charcoal filters were used to provide better tasting water (reference 2). Centuries later Hippocrates designed a cloth bag known as the Hippocrates Sleeve, used to remove sediments from water after boiling. By the end of the Middle Ages, water quality began to be linked with disease. In the mid 19th century, the spread of Cholera was noticeably decreased where sand filtration was utilized (reference 2). The benefits of water filtration for not only increasing water aesthetics, but decreasing the spread of disease, lead to the widespread use of filtration seen today when purifying water for potable use.

Current Use of Filtration for Water Treatment

The original slow sand filtration developed centuries ago has now been replaced with rapid sand filtration using multi-media beds, adsorption, utilizing electrochemical forces to attract contaminants to the media surface, natural and synthetic membranes engineered with distinct pore sizes, and ion exchange, where one ion is removed from the water and replaced with a less offensive ion. Current U.S. Army field water treatment includes several filtration devices such as the Reverse Osmosis Water Purification Unit, Tactical Water Purification System, and Lightweight Water Purifier, designed for large volume water purification. An industry challenge has been to reduce the size of full-scale filtration processes down to individual units, while maintaining treatment efficacy against pathogens and particulate matter, but without excessive maintenance. To date, there have been no IWPDs fielded to the Soldier that have used filtration as the primary mechanism of water purification. Currently fielded emergency drinking water products include an iodine-based disinfection tablet (Globaline™) and a flocculant-chlorine disinfectant based product (Chlor-Floc™). Today, there are several Commercial-Off-The-Shelf (COTS) IWPDs that use filtration as the primary pathogen reduction mechanism. (Globaline™ is a trademark of Wisconsin Pharmacal Company; Chlor-Floc™ is a trademark of Control Chemical, D/B/A Deatrick and Associates Inc.)

SEPARATION MECHANISMS

The mechanisms of separation during filtration vary depending on material and design. Overall, several mechanisms may be simultaneously rejecting contaminants. For example, during filtration primarily incorporating size exclusion, adsorption and depth filtration mechanisms are likely aiding in particle retention.

Straining

Straining entails the removal of particles by size exclusion when particles are larger than the void spaces in the filter. Straining is a removal mechanism for virtually all filtration technologies with the importance of this mechanism related to raw water quality and size of particulate matter in reference to pore size.

Straining by Granular Media

For spherical granular media, close-packed arrangement will remove particles when the ratio of particle diameter to grain diameter is greater than 0.15 (reference 3). For typical slow sand filters, this equates to the removal of particles down to about 15 µm, increasing to 30-80 µm for rapid sand filtration. It should be noted that other mechanisms aid in the removal of smaller particles for these filtration techniques.

Specifically, for slow sand filtration a thin slimy layer of particulate sludge forms, termed smutzdecke, effective in trapping particulates and microorganisms at the surface. When particulates form a layer during granular media filtration it may also be termed a cake. Cake filtration is often used to describe straining out particles, often smaller than the media pore size, by this top layer, or build-up, when evaluating granular carbon filtration.

Straining by Membrane Filtration

Porous membranes contain varying size pores and are rated by their pore size based on nominal, average, and absolute size. Absolute pore size is the size of the largest particle (e.g., glass bead) that will pass through a membrane under specific testing conditions. For membranes with uniform cylindrical pores this rating has meaning, but only under the low pressure conditions tested during pore size determination. Membranes with cylindrical pore structures are called capillary-pore membranes. Conversely, some membranes are manufactured to create a tortuous path (sponge-like appearance, termed tortuous-pore membranes) where pores of varying size create a path by which depth filtration mechanisms arise as well as size exclusion. In this case, the term absolute pore size has little meaning, and nominal ratings are used. Nominal pore ratings specify the percentage of particles removed of a certain size particle, again usually tested with glass beads (e.g., 80 percent of 1 μm particles retained). Lastly, membrane pore size can be rated as the average size of all pores. Different pore size testing techniques, as well as varying definitions, create a questionable pore rating system unless proper information on the membrane is noted. For example, it has been noted that certain manufacturers state absolute pore sizes when a membrane can remove 85 percent of a certain size particle, contrasting the historical definition of an absolute pore rating. Caution, therefore, must be used when evaluating membrane efficacy based solely on stated pore size.

Depth Filtration Theory

Particle removal and retention within depth filters involves Van der Waals forces where two surfaces have attractive forces, in this case between the particle and the media surface. Van der Waals forces are short-ranged, and only become effective when the two surfaces are in close proximity. For particle-media surfaces to come close enough together for these forces to become effective, transport mechanisms must be present. These mechanisms are represented by three different processes, which include interception, inertia and sedimentation, and diffusion. These processes are attributed with most particle removal. As a particle is transported through a filter, if the streamline is within one half or less of the diameter of the particle from the media surface, the particle will be intercepted. Second, as streamlines curve around the media, particles can deviate from the streamline and continue towards the media due to inertia forces. Particles may also deviate from streamlines due to gravitational forces and settle onto the media surface. In both cases, particle will be retained at the media surface. Lastly, particles may deviate from streamlines due to Brownian motion and diffuse to the media surface. The following diagram, Figure 1 (borrowed from reference 3), illustrates the different filtration mechanisms described. Depth filtration is not limited to granular media, but can be applied to microfilters, membranes and carbon filtration as well.

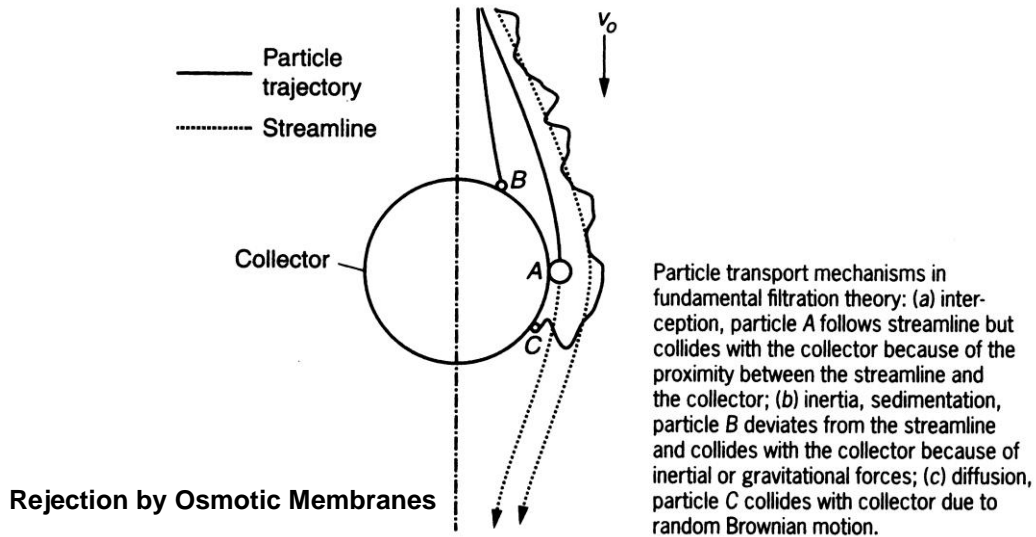


Figure 1. Filtration Mechanisms.

(Source: Reference 3)

Two solutions in contact with one another with varying solute concentrations naturally try to equilibrate. In water treatment we can use this driving force to equilibrate, by placing a semi-permeable membrane between the two solutions. By engineering the membrane to allow passage of the water molecules through the membrane, yet reject the solutes, the two solutions will naturally equilibrate as the water dilutes the more concentrated side. Flux through the membrane will vary based on solute gradient, temperature, and membrane properties. Common practice in water treatment is to reverse the natural osmotic tendency by pressurizing the influent side, forcing water molecules through the membrane and rejecting the solutes, termed reverse osmosis (RO). Despite use in water treatment for many years, the exact mechanism of water transport and solute rejection is still debated. The underlying question is whether these membranes are non-porous and diffusion driven, or whether they contain very small pores for preferential (size exclusion) convective transport of the solvent. There are several theories, or models, on the rejection mechanisms of osmotic membranes of which three are most commonly accepted.

Solution-Diffusion Model

The solution-diffusion model describes permeation through a dense membrane that is permeable but non-porous. Water and solutes dissolve into the membrane, diffuse through the solid material, and re-liquify on the permeate side. In this model, separation occurs due to the different flux of solutes.

Pore Flow Model

This model considers convective flow through a porous membrane. Water and solute flux is coupled with separation occurring due to sieving. Since many solutes, namely salt, are similar in size to water molecules, physical sieving would not be efficient. An apparent limitation of this model is the small pore size required, less than 0.1 nanometer (nm), for separation to occur.

Preferential Sorption-Capillary Flow Model

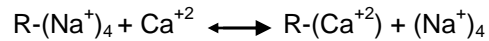
This model describes a porous membrane where water is preferentially sorbed to the surface and transported through the membrane due to concentration gradient. Membranes with low dielectric constants prefer water molecules, creating a layer of low solute concentration, in essence blocking the solutes from contact with the membrane surface and therefore preventing passage. Osmotic potential, to pull water across a membrane from a less to more solute concentrated side, has also been applied to IVPDs in a passive form. By using a non-offensive solute on the membrane product side, water will naturally pass across the membrane to the higher solute concentration. Sometimes termed forward osmosis, this process, simply termed osmosis (O) for this paper, utilizes the same pathogen reduction mechanisms as that of conventional RO.

Adsorption

Adsorption is a mass transfer operation in which contaminants present in a liquid phase are accumulated on a solid phase, thereby being removed from the liquid. The constituent being adsorbed is referred to as the adsorbate and the solid onto which the constituent adsorbs is the adsorbent. The degree of adsorption is affected by attraction of the three following interfaces: adsorbate/adsorbent, adsorbate/water, water/adsorbent. The strength of the adsorbate/adsorbent interface as compared to the others will determine adsorption efficacy. Dissolved species are concentrated onto the surface by physical attraction or chemical reaction. Physical adsorption is by nonspecific binding mechanisms such as Van der Waals forces. This binding is reversible, where adsorbates may desorb in response to a decrease in solution concentration. Chemisorption entails specific attraction where chemical binding transfers electrons between the adsorbent and adsorbate. Physical adsorption has weaker forces and bonding energies, operates over longer distances, and is more reversible than chemical adsorption. Chemical adsorbates, which can only form a layer one molecule thick due to specific bonding, may have several different attractive forces. Polar compounds having a slightly positive and negative end and molecules orient themselves to lower their combined free energy, creating a dipole attraction. The negative end attracts the positive end of another molecule forming a dipole-dipole bond. More important to water treatment is the dipole-dipole bond with water, termed hydrogen bonding. These bonds are very strong and are responsible for water being a liquid at room temperature. Hydrogen bonding between the water molecule and adsorbate competes with adsorbate/adsorbent attraction. By maximizing physical attraction, covalent bonding and Coulombic forces, all of which are not involved in adsorbate/water, water/adsorbent interaction, we can increase adsorption efficacy. Water pH, molecule size, and adsorbate solubility all play roles in adsorption and affect species (polar, neutral, ionic) differently. Since adsorption is not a primary mechanism for pathogen reduction these interactions will not be further discussed but can be found elsewhere (references 3-5). During the adsorption process, dissolved species are transported into the porous structure of the adsorbent material by diffusion, then adsorbed onto the interior surface of the grain. Porous adsorbent materials have very large internal surface areas (400 – 1500 meters squared per gram (m^2/g)), and pore volume (0.1 – 0.8 milliliters per gram (mL/g)) (reference 3) creating many sites for adsorption to occur. Three commonly used commercial adsorbents include zeolites (aluminosilicates), synthetic polymeric adsorbents, and activated carbon. A notable affect on adsorption with the most common adsorbent, activated carbon, is water pH. In order for electrostatic interactions to contribute to removal by adsorption, particle-media charges must attract the particle to the media surface. Since most particles in natural waters possess a negative charge, media should possess a positive charge. As pH increases, activated carbon becomes less positive until a point of zero charge (PZC) is reached (reference 4). At a pH above this point, electrostatic interactions repel particles from the surface, inhibiting adsorption. Depending on the carbon used the PZC may range from a pH of less than 4 up to greater than 10 (reference 4).

Ion Exchange

Ion exchange for drinking water is a process in which ions within the water stream are adsorbed to the surface of resins and exchanged for a less offensive ion that is then imparted into the finished water. A generic representation of softening using a sodium resin is shown below, with R representing the exchange resin.



Similar to adsorption, ion exchange is powered by electrostatic/electrochemical attraction in which ions of opposite charge attract, however, with ion exchange, the presaturant ions on the resin are released into the water. For ion exchange to occur, the presaturant ions cannot be present in the bulk fluid. Natural tendency to equilibrate will favor ions both in the bulk fluid as well as on the resin surface, therefore equilibrium will occur if given enough time (reference 6). Resin beads are usually 0.04 to 1.0 mm in diameter and made by materials such as polystyrene divinylbenzene. Favorable ion exchange resins are reversible, and once all exchange sites are exhausted they can be restored through regeneration, although eventually irreversible fouling will occur. Regeneration usually consists of several bed volumes of highly concentrated regenerant followed by rinse water. To date, the most common use of ion exchange has been for softening, although heavy metal reduction and resins designed for specific ion reduction are also becoming more commonplace. There are four common ion exchange resins, classified as either strong-acid cation, weak-acid cation, strong-base anion, or weak-base anion. The cation exchange resins are negatively charged resins often used for calcium and magnesium removal, while the less common anion resins are positively charged for the removal of nitrate and other anions. Both strong-acid and strong-base resins are effective throughout all pH ranges, with the weak-acid and base resins effective only within narrow alkaline and acidic pH regions, respectively. The preference of the ion exchange resin to attract one ion over another is termed its selectivity sequence. Ions are ranked based on separation factors, or the ratio of the affinity of the resin to favor the ion compared to the presaturant ions already attached to the resin. In general, with dilute solutions, ion exchange resins prefer ions with the highest charge and lowest degree of hydration. If both anion and cation removal is required, different resins can be run in series or mixed bed resin columns can be used to produce deionized water. In this case, strong-acid resin of the H⁺ form and strong-base resin of the OH⁻ form are mixed with the resultant presaturant ions released forming water. In this case no ions are imparted to the finished water. A major drawback of mixed bed resins is that the resin must be separated before regeneration can occur. Since IWPDs are not designed to be regenerated, these drawbacks are not applicable.

ROLE OF PATHOGEN IN FILTRATION SEPARATION MECHANISMS

The primary difference between pathogens for reduction during filtration is size. Approximate sizes are as follow: viruses 0.005 – 0.3 μm, bacteria 0.1 -10 μm, *Cryptosporidium* oocysts 4 – 6 μm, *Giardia* cysts 8 – 12 μm. Common filters used in IWPDs have pore sizes between 0.2 and 2 μm, although some exist outside of this range. Primary reduction mechanisms for each pathogen vary with purification technology, with generalizations based on pathogen morphology as follows. (1) Based on size exclusion alone, filter retention of *Cryptosporidium* oocysts and *Giardia* cysts is likely for properly functioning devices. It is generally assumed that if a filter can reduce *Cryptosporidium* oocysts then *Giardia* cyst reduction is likely (reference 7). Utilizing filters where the primary means of reduction is by size exclusion, latex microspheres have been used as surrogates, demonstrating the lack of importance of other mechanisms for cyst reduction (references 1, 8). (2) Bacterial reduction by filters is based on adsorption as well as size exclusion (reference 9). Reduction by microporous media with pore sizes of 0.45 μm or less will likely provide adequate bacterial reduction based on size exclusion alone. Clean bed filtration, utilizing larger pore sizes will likely not meet the bacterial reduction requirements of references

1 and 10. (3) Due to the extremely small size of viruses, reduction by size exclusion to the levels required in references 1 and 10 is unlikely, unless utilizing very tight membranes such as for osmosis. Extensive literature exists demonstrating viral adsorption onto microporous filters as well as how water quality affects viral reduction (references 9 and 11-24). Particles immersed in aqueous solutions, including viruses, develop a surface charge by adsorbing ions on its surface (reference 11). The charge of viruses has been shown to play a significant role in adsorption onto surfaces and this charge changes with pH. Similar to the ZPC of activated carbon, the pH at which viruses have no net charge is called the isoelectric point (pI). Below this pH, viruses are positively charged, and above this point they are negatively charged. Coupling filters that are positively charged at a pH where the viruses are negatively charged, with the difference in charge minimized (e.g., near both pI) promotes the most efficient adsorption (reference 12). From this, it is apparent that no single combination of adsorbent/adsorption conditions exists to give optimum reduction of all viruses for all water qualities (reference 12). Increasing electrostatic and or hydrophobic interactions by the addition of chemicals such as magnesium sulfate (reference 13) or by specially treating the filter to promote a positive charge at natural water pH will increase virus retention (references 14-17). One study investigating coliphage reduction by a 0.2 μm microporous filter, showed reduction based on adsorption as well as size exclusion (reference 9). Initial retention on clean bed filters was based on inertial impaction due to adsorptive forces, resulting in low to moderate reduction and highly affected by flow rates, water quality, and membrane material. As cake formed on the surface the primary reduction mechanism changed to direct interception at the surface due to reduction in pore size (reference 9). Reduction efficacy was less affected by water quality but still showed some susceptibility to changes in flow rate. Virus reduction by adsorption or size exclusion on capillary formed membranes is unlikely to consistently meet the requirements of reference 1.

IWPDs USING MEMBRANE FILTRATION

Membrane Filtration

A membrane is a thin layer of semi-permeable material that is capable of separating materials when a driving force is applied across the surface. This separation into two phases (concentrations) creates a chemical potential between the two sides of the membrane that is based on the physical and chemical properties of the materials being separated. Membranes are not considered to be passive materials but are termed functional materials whose performance characteristics are based on the nature of the elements to be separated and the driving force. Membranes are classified based on the size or molecular weight cutoff (MWCO) of the solutes they are capable of rejecting. Membranes used in water treatment, in order of decreasing pore size/MWCO, are microfilters, ultrafilters, nanofilters, and osmotic membranes. In addition to the pore size, membranes are also classified based on their structure, either symmetric or asymmetric. Symmetric membranes contain consistent pores, porosity, and transport properties. Asymmetric membranes contain complex pore structure with pore size, porosity, and transport properties changing with depth. Asymmetric membranes contain a thin active layer where separation occurs, supported by a thicker, more porous support structure to provide membrane integrity. Currently available IWPDs utilize micro and osmotic membrane filters. Membranes are complex materials and are often difficult to classify due to minor differences in materials and structure. The following information gives general information on the most common types of membranes used in IWPDs. Membrane configurations within IWPDs are commonly oriented as flat sheet, pleated sheet, or hollow fiber. With respect to pathogen reduction efficacy, membrane orientation is not a factor. Due to lack of information provided by manufacturers, and the proprietary nature of IWPDs, not all types of membranes found in IWPDs will be discussed.

Polymer Microfilter Membranes

Polymer microfilter membranes used in IWPDs are thin sheets up to about 200 μm thick or hollow fiber microporous membranes having diameters of 70 to 600 μm and thicknesses similar to thin sheet membranes. These membranes are engineered with specific properties for different applications and can be made of many materials. Common materials may be polycarbonate (PC), cellulose acetate (CA), or polyethersulfone (PES). Each material contains properties that affect membrane performance. In general, increasing hydrophilicity (contact angle less than 90 degrees, e.g., does not repel water molecules) will decrease fouling potential and increase flux. Membranes that are biologically inert, operate over a wide pH and temperature range, and are chemically resistant are the most desirable for water treatment. Detailed descriptions on the production of these membranes can be found in reference 25.

Microbial pathogen reduction mechanism by polymer microfiltration membranes is based on pore structure. Capillary-pore membranes, often made of PC, are thin (about 10 μm) and consist of uniform cylindrical pores, reject microbes based on size exclusion alone, and are generally given an absolute pore size rating. In theory, these membranes should reject all microbes greater than the pore size, but in practice, defects in pore size manufacturing as well as seams and seals within the device will prevent total rejection of larger organisms. During use, capillary-pore membranes will build-up rejected solids on the surface of the membrane. This build-up will decrease the effective pore size of the membrane and increase headloss. As this clogging increases, so does the ability of the membrane to reject microorganisms. Clean capillary-pore membrane microfilters have pore sizes down to 0.1 μm , which can be expected to reject bacteria and protozoan cysts, but have minimal effect on virus reduction. In contrast to capillary-pore membranes, tortuous-pore membranes are thick (about 150 μm), consist of sponge-like structure where sieving as well as depth filtration mechanisms dominate, and have increased flux over capillary-pore membranes. These are often made of CA or PES. Pore sizes vary with depth and spatially with direction. In addition to sieving, microbes are adsorbed onto the media as described in the above sections on depth filtration theory and adsorption. Due to more efficient separation mechanisms, these membranes have been shown to retain particles orders of magnitude smaller than the nominal pore size (reference 25). Tortuous-pore membranes, like capillary-pore membranes, have pore sizes down to about 0.1 μm , making these efficient at retaining bacteria and protozoan cysts, but not effective at sieving viruses. Due to the adsorptive nature of these membranes, it has been shown that several log virus reduction can be achieved but results are inconsistent and drop with continued production (references 3 and 25). Polymer microfilter membranes are very effective at reducing particulate matter and based on pore size should be able to reduce water turbidity to below 1 nephelometric turbidity unit (NTU). Due to the small pore size of these membranes they are prone to fouling, especially with the dead-end configurations used in IWPDs. Pre-filtering and a cleanable or backwashable configuration will reduce fouling.

Osmotic Membranes

Osmosis uses pressure, RO or solute gradient osmosis, to drive the solvent through a dense, nonporous membrane (some models consider a porous membrane) that will retain salts and solutes down to very low molecular weights. Natural osmotic pressure induces travel from a less to a more concentrated solution. A pressure, in excess of the osmotic potential, must be applied to reverse this flow (RO). Osmotic potential is a function of the molar concentration of the solute. In essence, smaller molecules create higher osmotic potentials. Pressures to reverse this natural tendency can be high. Twice the osmotic pressure is common in design with seawater separations, with pressures of 5 to 8 MP are typically used. The mechanism of separation for RO is solution/diffusion + exclusion as explained above. Separation is based on the solubility and diffusivity of materials in the membrane. RO membranes are usually made of hydrophilic cellulose acetate materials, cellulose ester plastics, or composites such as a cross-linked

polyamide on a polysulfone and fabric base. CA membranes along with other non-composite membranes are termed asymmetric. The entire membrane is composed of the same material with the pore size decreasing as you approach the surface. In nonporous asymmetric membranes, the surface skin is dense with a porous support membrane underneath of the same material. Composite membranes are anisotropic where the top layer and sublayer originate from different material. The top dense layer sits on top of a porous material, usually an asymmetric membrane. Composites can be designed for certain selectivities, but presently are less common than CA. CA membranes can resist a low level chlorine residual, but are very susceptible to biological degradation. RO membranes are very thin ranging from 0.25 to 4 μm to increase flux through the membrane as flux is inversely proportional to membrane thickness. They operate ideally at pH 4 to 6.5 and at temperatures below 30 (degrees Celsius) $^{\circ}\text{C}$. Water flux increases with temperature as long as temperature remains within the ideal range of the membrane material. Membrane configuration may be plate and frame, spiral-wound, tubular, or hollow fine fiber. The most common configuration, spiral-wound, contains sheets of membranes separated by spacer sheets then rolled together around a feedwater spacer. The hollow fine fiber configuration is similar to that used for microfiltration but incorporating tighter membranes. Increased surface area, resulting in higher flux, and less fouling are benefits of the hollow fine fiber design.

Osmotic membranes are classified based on MWCO with mechanisms of removal described in an above section. Measured in dalton, these membranes are capable of rejecting molecules with a mass of > 100 dalton regardless of charge. Generally speaking rejection efficacy favors multivalent ions, branched isomers, and increasing molecular mass. Based on size exclusion alone, osmotic membranes are capable of retaining species as small as $0.0001 \mu\text{m}$ (reference 26). These membranes can remove most all natural water contaminants known, although no treatment can universally remove everything. Microorganisms, salts, hardness, and organic chemicals, among many others can be removed, whereas most dissolved gases such as hydrogen sulfide and carbon dioxide will not be removed (reference 26). IWPDS utilizing osmotic membranes are historically designed for salt water desalination. With the introduction of IWPDS using osmosis, application to fresh water has been considered. Currently, IWPDS using RO or O should be capable of reducing waterborne pathogens (bacteria, cysts, and viruses) to levels considered acceptable for human consumption, as recommended by the EPA (reference 1). Devices using osmotic membranes will produce the lowest NTU water of all membrane materials. IWPDS using RO are historically not designed for natural water purification where turbid water may quickly foul the membrane. RO units will perform most efficient for desalination were particulate matter is not a concern. RO use in IWPDS for natural waters would require very efficient pre-filtering, as by another membrane process such as microfiltration, and is therefore not considered a viable technology. IWPDS using O will also produce extremely low NTU water and will not be affected by particulate matter regardless of natural water turbidity. Since O devices do not use pressure to force water through the membrane, no cake is formed at the media surface and no pre-filtering is required.

IWPDS USING CERAMIC MICROFILTRATION

Ceramic microfilters are made from inorganic ceramic pastes derived from powders of alumina (Al_2O_3), zirconia (ZrO_2), and titanium (TiO_2). These pastes are extruded and sintered at high temperature to form membrane supports with macro pores. Subsequently, submicronic powders are laid on the supports to create smaller pore diameters. This process creates a symmetric material with high chemical, mechanic, and thermal resistance that can be formed in a variety of shapes including candles, discs, and tubes (reference 27). Pore structure is tortuous path depth filtration with symmetric pores throughout the depth of the filter. With pore sizes down to $0.1 \mu\text{m}$, ceramic microfilters are efficient at retaining bacteria and cysts through adsorption and depth filtration mechanisms. At the household level utilizing untreated water sources, ceramic filter use has been shown to reduce coliform bacteria resulting in greater than 70 percent reduction in cases of diarrhea (reference 28). As with other microfilters, no mechanism exists to adequately reduce virus concentrations. Commercially available ceramic microfilters are often

impregnated with silver to discourage microbial growth on the media surface. This is intended solely to limit growth on the media and will have no effect on bulk water pathogen reduction. Ceramic microfilters are very effective at reducing particulate matter and based on pore size should be able to reduce water turbidity to below 1 NTU. Due to the small pore size of these filters they are prone to fouling, especially in dead-end configurations used in IWPDs. For IWPD use, ceramic filters are designed to be mechanically cleaned by scraping particulate build-up from the media surface. The ability to clean this media multiple times makes these filters a very effective, but high maintenance, technology for use with turbid waters. Due to the small pore size of these membranes, pre-filtering is required.

IWPDs USING FIBER AND FABRIC FILTRATION

Fiber and fabric microfilters can be made of compressed or cast fibers such as cellulose papers, woven fabrics, and glass, in addition to numerous other materials (reference 29). The most common to IWPDs are fiber microfilters made of material such as borosilicate glass. These filters are symmetric depth filters with pores sizes down to about 0.2 μm . Pathogen reduction follows depth filtration, adsorption, and straining mechanisms. Clean bed pathogen reduction may entail Van der Waals interaction and electrostatic interactions as well as straining based on size exclusion. After continued use, cake formation will likely make straining the predominant rejection mechanism. Consistent reduction of bacteria and cysts based on size exclusion is expected. No mechanisms exist to consistently reduce virus to the standards of reference 1. Fiber and fabric microfilters are very effective at reducing particulate matter and based on pore size should be able to reduce water turbidity to below 1 NTU. Due to the small pore size of these filters they are prone to fouling, especially in the dead end configurations used in IWPDs. With proper design, such as allowing for mechanical cleaning by way of scraping the surface, these filters can be highly effective at treating turbid waters. Non-cleanable filters, requiring replacement once clogged are not as desirable for turbid waters. Due to the small pore size of these membranes, pre-filtering is required.

IWPs USING CARBON FILTRATION

Carbon Filtration

Carbon used for water treatment can be of three different forms; granular, powdered, block. Granular activated carbon (GAC) for water treatment is often made from wood, peat, lignite, coal, or coconut shells. Manufacturing consists of carbonization and activation. Carbonization is conducted in the absence of air at temperatures up to 700 $^{\circ}\text{C}$, while activation, or oxidation, is accomplished at temperatures of 800 – 900 $^{\circ}\text{C}$ in the presence of oxidizing gases such as steam or CO_2 . Activation burns off anything volatile, leaving highly porous grains with large surface areas. Grain size varies with typical values between 0.4 mm and 2.5 mm. Powdered activated carbon (PAC) is made of the same materials as the granular form, but activation can entail either gas or chemical processes. The final product is powder with typical particle sizes ranging from 10 to 100 μm . Carbon block is produced by sintering powdered carbon, thermoplastic binders, and other additives. Material is extruded or molded under heat and pressure to form a hollow filter block of just about any shape or size. Absolute control over pore size is possible as well as engineering for specific contaminant reduction. Carbon blocks, unlike GAC, contain increased surface area, do not exhibit channeling, and contain an order of magnitude smaller pore size resulting in increased adsorption capacity (reference 30). Commercially available carbon block is often impregnated with silver to discourage microbial growth on the media surface. This is intended solely to limit growth on the media and will have no effect on bulk water pathogen reduction. When carbon adsorption capacity becomes exhausted, regeneration, involving the desorption of solutes from the media without affecting the media surface, and reactivation, entailing partial regeneration affecting the media surface, are conducted to restore the media for future use.

Pathogen Reduction

GAC has no specific mechanism for pathogen reduction beyond that typical of other granular media (reference 31). Typically larger in size than most filter media, pathogen and particulate removal by GAC is poorly accomplished by the straining and depth filtration mechanisms described in an above section. PAC, like GAC, is used for taste and odor reduction, and is not considered an effective barrier to pathogens. Carbon blocks have been shown to effectively reduce pathogens from water (references 32-34). Pathogen reduction by carbon blocks can follow any of the three generally accepted particle reduction mechanisms for porous media; cake filtration (surface retention), depth filtration, or adsorptive filtration. Depending on pore size, pathogens may be retained based on size exclusion alone. As cake forms on the media surface, exclusion of smaller particles due to decreased pore size is considered a predominant reduction mechanism (reference 33, 34). Carbon block surface charge may play an important role in clean bed filtration. The surface charge of carbon block is based on the pH at which the surface is not charged, called the PZC (reference 4). At pH below this point the surface is positively charged and above this point negatively charged. Since pathogens generally possess a negative charge, as pH decreases, reduction should increase due to electrostatic interactions. It has been shown that initial reduction due to electrostatic or Van der Waals attraction is followed by straining, as the negatively charged particles neutralize the surface of the carbon block (reference 32). When pH was above the PZC, pathogen reduction based on adsorption was ineffective. Proprietary chemically treated carbon blocks are available that have been shown to be capable of reducing bacteria, cysts, and viruses by the requirements of reference 1 (reference 32). Little is known about the proprietary chemical treatment and the exact pathogen kill mechanism is unclear. With respect to available IWPDs, carbon blocks with pore sizes of 1 μm or greater are common. Based on this, cyst reduction would be likely, and except for specially treated carbon blocks, consistent bacterial and viral reduction would not be expected to the reduction requirements of reference 1. Granular carbon filtration will retain some particulate matter based on particle size. As a cake forms on the surface, increased removal will occur. Clean bed granular carbon alone will not likely reduce water to less than 1 NTU. Carbon block filtration will reduce particulate matter with efficacy based on block pore size. Again, particulate size will be a factor in retention within carbon blocks which, as used currently in IWPDs, have a pore size of about 1-2 μm . Granular carbon will not likely be the limiting treatment technology requiring pre-filtering for IWPDs, as an additional pathogen reduction mechanism will be present that will dictate required pre-filtration. To reduce clogging, pre-filtering is beneficial when using carbon block, but not required as shown by current device configurations.

IWPs USING ION EXCHANGE

Ion exchange is not a proven technology for pathogen reduction. IWPDs utilizing ion exchange must employ an additional mechanism to adequately reduce microbial contamination. Microbial growth can occur within ion exchange beds, possibly resulting in increased contamination due to microbial growth sloughing into the effluent stream. One non-conventional ion exchange process has shown much promise at inactivating pathogens. Iodine ion exchange resins, primarily of the tri-iodide or penta-iodide form, have been extensively studied and are considered effective at pathogen inactivation through disinfection mechanisms (references 29, 35). Ion exchange is not designed for, and will not be effective at, reducing particulate matter. Pre-filtering is necessary to avoid fouling of the resin.

CONCLUSION

The effectiveness of filtration as the primary mechanism to reduce pathogens in IWPDs is based on the technology used as well as the raw water quality. Filtration utilizing microporous filters primarily reduces pathogens by size exclusion due to surface or depth filtration mechanisms. Adsorptive interactions contribute to pathogen reduction during the initial filtration until cake formation occurs where charge neutralization limits the effectiveness of this mechanism. For IWPDs using size exclusion as the

reduction mechanism, bacteria and cyst reduction is possible dependant on pore size. The small size of viruses prevents retention by size exclusion to the reduction requirements for purifying natural water. Adsorption of viruses has also been shown to be inadequate to consistently meet requirements for producing microbiologically safe water. Carbon filtration performs similar to granular or microporous filters with equivalent pore sizes. Proprietary chemically treated carbon surfaces have been shown to meet reduction requirements for microbiologically safe water but may be sensitive to water characteristics such as pH. IWPDs using osmotic membranes are the most effective at reducing pathogens although pressure driven osmotic devices will quickly foul when used with fresh water sources. For IWPDs, filtration will decrease the particulate matter present in turbid water with efficacy based on pore size. The ability of the IWPD to perform properly with turbid water sources is dictated by the pre-filter configuration and ability to clean the media surface.

Table. Summary of the Pathogen Reduction Efficacy and the Effect of Particulate Matter on IWP Filtration Technologies

Technology	Summary
Membrane Microfilter	Expected effectiveness at reducing bacteria and cysts. Microfilter pore size too large to adequately reduce viruses, requiring additional treatment. Common configurations limit the effectiveness of membrane surface cleaning making this technology susceptible to fouling from particulate matter. Degree of fouling directly related to efficacy of pre-filter. Straining as well as depth filtration mechanisms may be involved in microbial and particulate rejection based on membrane structure.
Ceramic Microfilter	Expected effectiveness at reducing bacteria and cysts. Microfilter pore size too large to adequately reduce viruses, requiring additional treatment. Ability to scrape rejected material from the microfilter surface enables flow to be restored after fouling. Frequency of cleaning, and length of filter useful life directly related to efficacy of pre-filter. Straining as well as depth filtration mechanisms can be involved in microbial and particulate rejection.
Fiber/Fabric Microfilter	Expected effectiveness at reducing bacteria and cysts. Microfilter pore size too large to adequately reduce viruses, requiring additional treatment. Filters designed to be cleanable should provide some ability to restore flow after fouling. Frequency of cleaning, and length of filter useful life directly related to efficacy of pre-filter. Non-cleanable filters highly susceptible to fouling. Straining as well as depth filtration mechanisms may be involved in microbial and particulate rejection.
Reverse Osmosis	Effective at reducing bacteria, viruses, and cysts. Technology is not designed to treat fresh water sources and, therefore, requires very effective pre-filtering to prevent membrane fouling. Not a feasible IWP technology for microbial or particulate reduction of fresh water.
Osmosis	Effective at reducing bacteria, viruses, and cysts. Technology is passive, eliminating the fouling effects of turbid water, and eliminating the need for pre-filtration. Slow production of fluid, exacerbated by cold temperatures.
Granular/Powdered Carbon	Not considered effective at reducing bacteria, viruses, or cysts. Granular media is often too large to effectively reduce pathogens based on size exclusion and is not considered effective at depth filtration mechanisms. Powdered carbon is used solely for taste and odor reduction and is not effective at pathogen reduction. Particulate matter affects these technologies similar to conventional granular media.

Table. Summary of the Pathogen Reduction Efficacy and the Effect of Particulate Matter on IWP Filtration Technologies (continued)

Technology	Summary
Carbon Block	Expected effectiveness at reducing cysts. Consistent reduction of bacteria is not expected due to the pore size of carbon blocks commonly used in IWPs. Not effective at adequately reducing viruses, although proprietary media has shown some promise. Pathogen reduction based on size exclusion and depth filtration mechanisms. Effects of particulate matter similar to other technologies of similar pore size. Pre-filtration and cleanable filters will decrease fouling from particulate matter.
Ion Exchange	Not considered effective at reducing bacteria, viruses, or cysts. Iodine ion exchange resins have been proven effective at pathogen inactivation through disinfection mechanisms. Particulate matter fouls ion exchange resin and therefore prefiltration is necessary.

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DATED: March 2006, updated January 2011

APPENDIX A REFERENCES

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