

year or two), the need for a reliable source of electricity to power the lamps, the need for period cleaning of the lamp sleeve surface to remove deposits and maintain UV transmission, especially for the submerged lamps, and the uncertainty of the magnitude of UV dose delivered to the water, unless a UV sensor is used to monitor the process. In addition, UV provides no residual chemical disinfectant in the water to protect against post-treatment contamination, and therefore care must be taken to protect UV-disinfected water from post-treatment contamination, including bacterial regrowth or reactivation.

3.9 Costs of UV disinfection for household water

Because the energy requirements are relatively low (several tens of watts per unit or about the same as an incandescent lamp), UV disinfection units for water treatment can be powered at relatively low cost using solar panels, wind power generators as well as conventional energy sources. The energy costs of UV disinfection are considerably less than the costs of disinfecting water by boiling it with fuels such as wood or charcoal.

UV units to treat small batches (1 to several liters) or low flows (1 to several liters per minute) of water at the community level are estimated to have costs of 0.02 US\$ per 1000 liters of water, including the cost of electricity and consumables and the annualized capital cost of the unit. On this basis, the annual costs of community UV treatment would be less than US\$1.00 per household. However, if UV lamp disinfection units were used at the household level, and therefore by far fewer people per unit, annual costs would be considerably higher, probably in the range of \$US10-100 per year. Despite the higher costs, UV irradiation with lamps is considered a feasible technology for household water treatment.

4. Physical removal processes: sedimentation and filtration

4.1 Microbe size and physical removal from water

Microbes and other colloidal particles can be physically removed from water by various processes. The sizes of the microbes are especially important for their removal by sedimentation and filtration. Viruses are the smallest waterborne microbes (20 to about 100 nanometers in size) and the most difficult to remove by filtration and other size exclusion methods. Bacteria are somewhat larger than viruses (about 0.5 to 3 micrometers) but too small to be readily removed by plain sedimentation or settling. Protozoan parasites are the next largest in size (most are about 3 to 30 micrometers) and only the largest ones are likely to gravity settle at appreciable rates. Protozoan removal efficiency by filtration varies with parasite size and the effective pore size of the filter medium. Helminths are multicellular animals, but some are important waterborne pathogens because their eggs (ova) and waterborne larval stages can be waterborne. Most helminths of concern in water are large enough to gravity settle at appreciable rates; they are readily removable by settling and various filtration processes.

Although viruses, bacteria and the smaller protozoans are too small to gravity settle, these waterborne pathogens are often associated with larger particles or they are aggregated (clumped). Aggregated or particle-associated microbes are easier to remove by physical processes than the free or dispersed microbes. Consequently, observed reductions of waterborne microbes by physical removal processes are

sometimes greater than expected or anticipated based strictly on their individual sizes. In some situations, efforts are made to promote the association of pathogens with larger particles, such as by coagulation-flocculation, to promote their physical removal. Such methods will be described in later sections of this report.

4.2 Plain sedimentation or settling

The microbial quality of water sometimes can be improved by holding or storing it undisturbed and without mixing long enough for larger particles to settle out or sediment by gravity. The settled water can then be carefully removed and recovered by decanting, ladling or other gentle methods that do not disturb the sedimented particles. Sedimentation has been practiced since ancient times using small water storage vessels or larger settling basins, reservoirs and storage tanks. The advantages and disadvantages of plain sedimentation for household treatment of water are summarized in Table 8.

Table 8. Advantages and Disadvantages of Plain Sedimentation for Household Water Treatment

Advantages	Disadvantages	Comments
Simple, low cost technology to reduce settleable solids and perhaps some microbes for water	Only settleable solids, such as sands, silts and larger microbes settle efficiently; clays and smaller microbes do not settle; only moderate to low microbe reductions	Can be applied to large and small volumes of water using commonly available water collection and storage vessels; settled material must be removed and vessels cleaned regularly
Removal of settleable solids can reduce turbidities and make the water more amenable to other treatment methods to reduce microbes	In some waters solids are not efficiently removed by settling and alternative methods of removing solids are required	Reduced levels of solids (turbidity) improves penetration of UV radiation (from sunlight), decreases oxidant (e.g., chlorine) demand, decreases solids-associated pathogens
Recommended as a simple pre-treatment of household water prior to application of other treatments to reduce microbes	Unreliable method to reduce pathogens; solids are not efficiently removed by settling from some waters; can be labor-intensive	Pre-treatment to remove solids (turbidity) is recommended for turbid waters prior to solar or chemical disinfection

Storing water for as little as a few hours will sediment the large, dense particles, such as inorganic sands and silts, large microbes and any other microbes associated with larger, denser particles. However, clay particles and smaller microbes not associated with large or dense particles will not settle under these conditions. Longer settling times, such as overnight or for 1-2 days, will remove larger microbes, including helminth ova and some parasites, some nuisance microbes, such as certain algae, and the larger clay particles. Most viruses and bacteria and fine clay particles are too small to be settled out by simple gravity sedimentation. Therefore, microbial reductions by plain sedimentation or gravity settling are often low and inconsistent. Overall reductions of viruses and bacteria by sedimentation rarely exceed 90%, but reductions of helminth ova and some protozoans can exceed 90%, especially with longer storage times of 1-2 days.

Sedimentation of household water can be done in simple storage vessels, such as pots and buckets. Care must be taken to avoid disturbing the sedimented particles when recovering the supernatant water by decanting or other methods. Typically, at least two containers are needed to settle water: one to act as the settling vessel and another to be the recipient of the supernatant water after the settling period. Water also can be

settled in larger bulk storage systems, such as cisterns, basins and tanks. Regardless of the sedimentation vessel, it is essential that solids are removed and the vessel cleaned on a regular basis. When water is sedimented in small collection or storage vessels, the sediment should be removed and the vessel cleaned after each use. At minimum, cleaning should be by rinsing with freshly collected source water. More rigorous physical or chemical cleaning is recommended to avoid the microbial colonization of the vessel surfaces and the resulting accumulation of a biofilm. For sedimentation in larger, stationary vessels and basins, such as cisterns and sedimentation tanks (some of which are designed to collect and store water for individual or small groups of households), protection of the water during storage, sanitary collection of the supernatant water after settling, and systems and procedures to clean the storage vessel also are critical

Sedimentation often is effective in reducing water turbidity, but it is not consistently effective in reducing microbial contamination. However, turbidity reductions often improve microbial reductions by physical and chemical disinfection processes, such as solar treatment and chlorination, respectively. Hence, plain sedimentation or gravity settling of highly turbid water for household use is recommended as a pre-treatment for systems that disinfect water with solar radiation, chlorine or other chemical disinfectants. Furthermore, sedimentation of particles improves the aesthetic qualities of the water and thereby increases its acceptance by consumers. Pre-treatment of turbid household water by sedimentation is recommended because is easy to perform and requires a minimum of materials or skill. It can be done with as little as two or more vessels by manually transferring (e.g., pouring and decanting) the water. For turbid waters containing non-settable solids, sedimentation will be ineffective and alternative methods of particle removal, such a filtration, are needed.

4.3 Filtration

Filtration is another ancient and widely used technology that removes particles and at least some microbes from water. As shown in Table 9, a variety of filter media and filtration processes are available for household or point-of-use treatment of water. The practicality, ease of use, availability, accessibility and affordability of these filtration media and methods vary widely and often depend on local factors. The effectiveness of these filtration methods in reducing microbes also varies widely, depending on the type of microbe and the type and quality of the filtration medium or system

Table 9. Filters and Filtration Media for Treatment of Household Water: Characteristics, Advantages and Disadvantage

Type Of Filtration	Media	Avail-ability	Ease of Use	Effectiveness (comments)	Cost
Granular media, rapid rate depth filter	Sand, gravel, diatomaceous earth, coal, other minerals	High	Easy to Moderate	Moderate* (depends on microbe size and pre-treatment)	Low to moderate
Slow sand filter	Sand	High	Easy to moderate (community use)	High** in principle but often low in practice	Low to moderate
Vegetable and animal derived depth filters	Coal, sponge, charcoal, cotton, etc.	Medium to high	Moderate to Difficult	Moderate*	Low to moderate
Fabric, paper, membrane, canvas, etc. filter	Cloth, other woven fabric, synthetic polymers, wick siphons	Varies: some low; others high	Easy to moderate	Varies from high to low (with pore size and composition)	Varies: low for natural; high for synthetics
Ceramic and other porous cast filters	Clay, other minerals	Varies: high- low, with materials availability and fabrication skill	Moderate. Must be physically cleaned on a regular basis to prevent clogging and biofilm growth	Varies from high to low (with pore size and ceramic filter quality)	Moderate to high
Septum and body feed filters	Diatomaceous earth, other fine media	Varies	Moderate to difficult; dry media a respiratory hazard	Moderate	Varies

* Moderate typically means 90-99% reductions of larger pathogens (helminth ova and larger protozoans) and solids-associated pathogens, but low (<90%) reductions of viruses and free bacteria, assuming no pre-treatment. With pre-treatment (typically coagulation), pathogen reductions are typically >99% (high).

**High pathogen reduction means >99%.

4.4 Granular media, rapid rate filters and filter media

Filtration through porous granular media, typically sand or successive layers of anthracite coal and sand, is the most widely used physical method for water treatment at the community level, and it has been used extensively for on-site treatment of both community and household water since ancient times (Oza and Chaudhuri, 1975; Chaudhuri and Sattar, 1990; Logsdon, 1990; LeChevallier and Au, 2002). A number of different granular media filters for household and other small-scale uses have been described, including so-called bucket filters, drum or barrel filters, roughing filters in the form of one or more basins, and above or below grade cistern filters. Granular media used for water filtration include sand, anthracite, crushed sandstone or other soft rock and charcoal. In recent years, efforts have been made to improve the performance of granular filter media for removing microbial contaminants by coating or co-mingling sand, coal and other common negatively charged granular media with metal oxides and hydroxides of iron, aluminum, calcium or magnesium (Chaudhuri and Sattar, 1990; Chaudhuri and Sattar, 1986; Prasad and Chaudhuri, 1989). Such modified media are positively charged and therefore, more effective for removing and retaining the negatively charged viruses and bacteria by electrostatic adsorption (Chaudhuri and Sattar, 1986). Some improved granular media filter-adsorbers have

incorporated bacteriostatic agents, such as silver, in order to prevent the development of undesirable biofilms that release excessive levels of bacteria into the product water (Ahammed and Chaudhuri, 1999). The production of these more advanced filter media containing charge-modified materials and bacteriostatic agents requires specialized skills and facilities, which are beyond the capabilities of most household users. Such media would have to be prepared and distributed to communities and households from specialized facilities. However, naturally occurring, positively charged granular media, such as naturally occurring iron oxide-coated sands or deposits of iron, aluminum, calcium or magnesium minerals, may be no more difficult or costly to obtain and prepare for household water filtration than otherwise similar negatively charged granular media.

A number of different designs and scales (sizes) of rapid, granular media filters are available for household and community water treatment. For household use bucket filters, barrel filters and small roughing filters are the main choices. The advantages and disadvantages of these filter designs are summarized in Table 10.

Table 10. Advantages and Disadvantages of Different Granular Medium Filters for Household Use

Filter Design or Type	Advantages	Disadvantages
Bucket filter	Useable on a small scale at household level; simple; can use local, low cost media and buckets; simple to operate manually; low (<90%) to moderate (90-99%) turbidity reduction	May require fabrication by user; initial education and training in fabrication and use needed; requires user maintenance and operation (labor and time). Commercial ones are relatively expensive. Low (<90%) pathogen reduction.
Barrel or drum filter	Useable on a small scale at household or community level; relatively simple; can use local, low cost media and barrels or drums; relatively easy to operate manually; low to moderate turbidity reduction.	Requires some technical know-how for fabrication and use; initial education and training needed; requires user maintenance and operation (some skill, labor and time). Low (<90%) pathogen reduction.
Roughing filter	Useable on a small scale at community level; relatively simple; can use local, low cost construction material and media; relatively easy to operate manually; low to moderate turbidity reduction	Less amenable to individual household use because of scale; requires some technical know-how for construction and use; initial education and training needed; requires user maintenance and operation (skill, labor and time). Low (<90%) pathogen reductions

4.4.1 Bucket filters

Bucket filter systems of granular media for household use usually require two or three buckets, one of which has a perforated bottom to serve as the filter vessel. The bucket with the perforated bottom is filled with a layer of sand, layers of both sand and gravel, or other media. Gravel and sand media of specified sizes often can be purchased locally. Alternatively, these media can be prepared locally by passing sand and gravel through metal sieves of decreasing mesh size and retaining the material in the appropriate size ranges (between 0.1 and 1 mm for sand and about 1-10 mm for gravel). Sand or other local granular media are placed in plastic or metal buckets approximately 2.5-gallon (10-liter) to 10-gallon (40-liter) capacity and having bottoms with perforations (punched with small holes and fitted with a mesh strainer, such as window screen or piece of cloth) to allow water to drain out. Buckets are

filled with several cm of gravel on the bottom and then a deeper layer of sand (about 40 to 75 cm) on top of the gravel. The granular medium bucket filter is suspended above a similar size empty bucket with a solid bottom to collect the water that drains from the filter as water is poured through it. The media of newly prepared bucket filters, as well as that of larger drum and roughing filters, must be cleaned initially with water to remove fine material and other impurities. So, the dirty water draining from new filters is discarded until the filtrate water has a low turbidity. The media of bucket filters must be cleaned or replaced on a regular basis to remove accumulated particles and to prevent the development of excessive microbial growths that will degrade water quality. The frequency of filter media replacement and cleaning depends on local conditions, but typically it is after a use period of perhaps several weeks.

A number of commercial sources of bucket filters are available and some have been used in both developing countries for small community and household water treatment. One of the better known and more widely distributed of these is the so-called commercial, two-bucket, point-of-use, media filter system. It consists of two 5-gallon plastic buckets with lids, filters and accompanying assembly fittings and contains both a particulate and a carbon filter. It is recommended that water be chlorinated before filtration. Use of chlorination adds complexity to the operation of the filter system and makes its use more difficult, less practical and more costly, especially for the developing world. The system sells for about \$US 50.00 and is designed to provide drinking water for up to 10 people per day. Replacement filter units are about \$US 20.00 plus shipping. These costs are beyond the means of the world's poorest people in developing countries. However, the commercial, two-bucket, point-of-use, media filter system has been subsidized and distributed in developing countries by NGOs and is used in small communities, primarily in disaster relief settings.

4.4.2 Drum or barrel filters

A number of different designs for drum or barrel filters having either up-flow or down-flow of water have been described for use as rapid granular medium filters. These filters are usually 55-gallon (about 200-liter) capacity steel drums and contain sand and gravel media similar to that used for bucket filters (Cairncross and Feachem, 1986; IDRC, 1980; Schiller and Droste, 1982). The filters generally have a cover to prevent the introduction of airborne and other contaminants. Down-flow filters have a perforated pipe at the bottom to collect the water passing through the medium and discharge it from the side of the drum. The outlet pipe for filtered water may discharge the water at the bottom of the drum or it may be configured with an upward bend or loop to discharge the water at the same level as the top of the media in the filter. Upward flow filters have a bottom inlet and a rigid perforated or porous plate to support the filter media, which is usually coarse sand. Water flows in an upward direction and is discharged through a side opening near the top of the drum. As with other granular media filters, the media of drum filters must be cleaned initially and on a regular basis. Cleaning down-flow filters tends to be technically more difficult and inconvenient. Water either has to be forced through the filter media in an up-flow direction in place, so-called backwashing, and the backwash water discarded, or the media has to be physically removed and replaced with cleaned or fresh media. Stopping the upward flow of product water and opening a bottom drain plug to discharge down-flowing dirty water that passes through the filter medium more easily

cleans up-flow filters. An upward flow granular medium filter consisting of two tanks in a vertical series, with the lower tank containing a layer of charcoal sandwiched between two layers of fine sand and the upper tank the collector of the filtrate has been designed by UNICEF to treat 40 L of water per day (Childers and Claasen, 1987). The extent to which this filter reduces microbial contaminants in water has not been reported. However, if it is anticipated these filters function as typical rapid granular media filters, pathogen reductions are likely to be no more than 90% and even less (~50%) for the smallest pathogens, the enteric viruses.

4.4.3 Roughing filters

Simple, low cost, low-maintenance, multi-stage roughing filters for household and community use have been described and characterized (Galvis et al., 2000; Wegelin and Schertenlieb, 1987; Wegelin et al., 1991). Typically, these filters are rectangular, multi-compartment basins constructed of concrete or other materials. They require modest skills for operation and maintenance, and therefore, are best suited for use by communities or at least multiple households. However, it is possible for these multi-compartment tanks to be centrally fabricated and distributed at low cost for placement and final installation at their locations of use. Many of these filters are designed to use two different sizes of low cost, coarse granular media in two or three compartments or stages, and such media are generally locally available. In a typical, design water flows horizontally (or vertically in either an upflow or downflow mode) into an initial chamber containing fine gravel or coarse sand and then into another chamber or (two successive chambers) containing coarse or medium sand having smaller particle sizes than the initial chambers and from which is then discharged as product water. For highly turbid water containing settleable solids, a horizontal or vertical sedimentation basin to remove this coarse material prior to filtration precedes the filter. The filter has provision for backwashing the medium from a valved inlet (at the bottom of the filter medium chamber in the horizontal and downflow filter designs). Roughing filters usually consist of differently sized filter material decreasing successively in size in the direction of flow. Most of the solids are separated by the coarse filter medium near the filter inlet, with additional removal by the subsequent medium and fine granular media in subsequent compartments. Roughing filters are operated at relatively low hydraulic loads or flow rates. Regular backwashing is required to main flow rates and achieve efficient particulate removals, and therefore, some skill and knowledge is required to properly operate and maintain a roughing filter. Removal of indicator bacteria by roughing filters has been reported to be 90-99%. Although not reported, it is expected that compared to bacteria removals, virus removals would be lower and parasite removals would be similar to or higher.

4.4.4 Filter-cisterns

Filter-cisterns have been in use since ancient times in areas heavily supplied with rainwater or other water sources but lacking land area for reservoir or basin storage (Baker, 1948). In this filtration system cisterns or large diameter well casings, partially below grade, are surrounded by sand filters, such that water flows through the sand and into the casing or cistern either from the bottom or through side of the casing near the bottom. Such filter-cisterns function as infiltration basins to remove turbidity and other particulates. Among the best known of these filter-cistern systems were those of the city of Venice, which date back at least several hundred years (to the mid-15th century). The sand filter rings were several meters deep and in the shape

of an inverted cone or pyramid in the center of, which was a cylindrical cistern or well casing that, collected the filtered water. The Venetian filter-cisterns were recognized for their ability to provide "clear and pure" water free "bad qualities". Today, filter-cisterns are being used in Sri Lanka to treat and store rainwater from roof catchment systems (Stockholm Water Symposium, 2000).

4.4.5 Biomass and fossil fuel granular media filters

Historically, depth filters composed of filter media derived from vegetable and animal matter have been employed for water treatment. Coal-based and charcoal filter media have been used since ancient times and carbon filter media are widely used today for both point-of-use and community water filtration systems (Argawal and Kimondo, 1981; Baker, 1948; Chaudhuri and Sattar, 1990). Filters containing sponges were widely used for on-site or point-of-use household and military water treatment in 18th century France. Water vessels had holes in their sides into which sponges were pressed, and water was filtered as it passed through the compressed sponges. Other filter designs consisted of sponges compressed into a perforated plate through which water was poured. Sponge filters imparted objectionable tastes and odors to the water unless they were cleaned regularly, indicating that microbial growths and biofilms probably were a major problem with these filters. Other media also employed in these point-of-use filters included sand, cotton, wool, linen, charcoal and pulverized glass, either individually or in various combinations as successive layers. These media also were used in larger scale filters for community water supply. Other examples of vegetable matter depth filters are those containing burnt rice hulls (as ash) or those consisting of vessels or chambers containing fresh coconut fibers and burnt rice husks in series (Argawal and Kimondo, 1981; Barnes and Mampitiyarachichi, 1983).

4.4.6 Microbial reductions by rapid granular media filters and recommended uses

Rapid granular media filters of the types described above are capable of reducing turbidities and enteric bacteria by as much as 90% and reducing larger parasites such as helminth ova by >99%. Because of their small size (typically <0.1 micrometer), enteric viruses are not appreciably removed by rapid granular media, with typical removals of only 50%-90%. These filters remove only viruses associated with other, larger particles or aggregated in larger particles. When roughing filters have been applied to highly turbid surface waters, removals have ranged from about 50 to 85% for bacteria and yeast's, with microbial removal efficiency depending on the type of filter medium (El-Taweel and Ali, 2000). The reduction of viruses and bacteria in rapid granular medium filters can be greatly increased (to >99%) if the filter medium is positively charged. This is accomplished by combining granular media such as coal (lignite, anthracite, etc.) with positively charged salts, such as alum, iron, lime or manganese. In positively charged filter media virus and bacteria reductions of 90->99% have been reported (Gupta and Chaudhuri, 1995; Chaudhuri and Sattar, 1990; Chaudhuri and Sattar, 1986; Prasad and Malay, 1989). Coal treated with alum or a combination of alum and silver was most effective for microbial reductions. Vegetable matter filters, such as those composed of burnt rice hull ash, have been reported to dramatically reduce turbidity, reduce bacteria by about 90% and require media replacement only every 2-4 months in southeast Asia (Argawal et al., 1981). Rice hull ash filters operated at a flow rate of 1 m³/m²/hr reduced *E. coli* by 90 to 99%, which was higher than the *E. coli* removal by a sand filter tested under similar

conditions (Barnes and Mampitiyarachichi, 1983). However, such vegetable matter filters, as well as many of the other designs of low cost granular media filters, have not been adequately evaluated for their ability to reduce a wide range of enteric pathogens, including enteric viruses, or their susceptibility to microbial growths and biofilms that can degrade the quality of the filtered water. Technological methods to modify granular media, such as chemical modification to impart positive surface charges, can improve microbial removals by filtration. However, such modifications are technically demanding to be applied at the household level and therefore, are recommended primarily for piped community water supply systems.

Overall, simple granular media filters, including bucket, barrel or drum and roughing filters, are appropriate technologies for water treatment at the community and perhaps the household level. They are effective in reducing turbidity but achieve only low to moderate microbe reductions, unless modified to make the media positively charged. Of these filter designs, the bucket filter is probably the most appropriate for household use because of its small scale, simplicity and manual application to quantities of water collected and used by individual households. Barrel or drum filters and roughing filters are more appropriate for community use or for sharing among several households within a community. However, none of these filtration methods achieve consistently high reductions of pathogens, unless chemically modified filter media are employed or the filtration process is combined with chemical disinfection such as chlorination. Therefore, granular media filters are best used at pre-treatment processes to reduce turbidity and provide product water that is more amenable to pathogen reductions by disinfection processes, such as solar radiation or chlorination. Due to their variable and potentially low microbe reductions, typical granular medium filters (not containing chemically modified media) are not recommended as a standalone treatment for household water supplies.

4.5 Slow sand filters

Slow sand filtration of drinking water has been practiced since the early 19th century and various scales of slow sand filters have been widely used to treat water at the community and sometimes local or household level (Cairncross and Feachem, 1986; Chaudhuri and Sattar, 1990; Droste and McJunken, 1982; Logsdon, 1990). Most are designed as either barrel filters, basins or galleries containing a bed of about 1-1.25 meter of medium sand (0.2 to 0.5mm) supported by a gravel layer incorporating an underdrain system. The filters operate with a constant head of overlying water and a flow rate of about 0.1 m/hour. Slow sand filtration is a biological process whereby particulate and microbial removal occurs due to the slime layer ("schmutzdecke") that develops within the top few centimeters of sand. Reductions of enteric pathogens and microbial indicators are relatively efficient and generally in the range of 99% or more, depending on the type of microbe. Therefore, microbial reductions by slow sand filtration can be high, if the filters are properly constructed, operated and maintained. However, slow sand filters often do not achieve high microbial removals in practice, especially when used at the household level. This is because of inadequacies in construction, operation and maintenance and the lack of institutional support for these activities.

Because of the development of the schmutzdecke and its accumulation of particles removed from treated water, the top layer (5-10 cm) of sand must be manually removed and replaced on a regular but usually infrequent basis. The removed sand is

generally cleaned hydraulically for later reuse. Labor to clean larger scale community sand filters has been estimated at 1 to 5 hours per 100 m² of filter surface area. Freshly serviced slow sand filters require time for reestablishment of the *schmutzdecke* or "ripening" to achieve optimum performance, and therefore, multiple filter units are recommended. The performance and operation cycles of slow sand filters is influenced by raw water quality. Highly turbid waters are difficult to filter directly and may require a pre-treatment procedure, such as sedimentation or roughing filtration, to reduce turbidity. Slow sand filters are an appropriate, simple and low cost technology for community water treatment in developing countries. However, they are not recommended for individual household use because of their relatively large size (surface area), and the needs for proper construction and operation, including regular maintenance (especially sand scraping, replacement and cleaning) by trained individuals. Such demands for achieving good performance are unrealistic because they are beyond the capacities and capabilities of most households.

4.6 Fiber, fabric and membrane filters

Filters composed of compressed or cast fibers (e.g., cellulose paper), spun threads (cotton) or woven fabrics (cotton, linen and other cloths) have been used to filter water and other beverages (e.g., wine) since ancient times. The use of wick siphons made of wool thread and perhaps other yarns to filter water was well known in the days of Socrates and Plato (about 350 to 425 BCE) (Baker, 1948). Various compositions, grades and configurations of natural fiber and synthetic polymer filter media materials continue to be widely used today for point-of-use and small community water supply systems. In their simplest applications these filters are simply placed over the opening of a water vessel through which particulate-laden water is poured. Another simple application is to place a cone shaped filter in a funnel through which water is poured and collected in a receiver vessel. The particles are removed and collected on the filter media as the water is poured into the vessel. Other paper and fibrous media filters are in the form of porous cartridges or thimbles through which water is poured to exit from the bottom, or alternatively, which are partially submerged in water so that filtered water passes to the inside and accumulates within. More advanced applications employ filter holders in the form of porous plates and other supports to retain the filter medium as water flows through it.

Paper and other fibrous filter media retain waterborne particles, including microbes, by straining them out based on size exclusion, sedimenting them within the depth of the filter matrix or by adsorbing them to the filter medium surface. Therefore, removal is dependent on the size, shape and surface chemistry of the particle relative to the effective pore size, depth and surface physical-chemical properties of the filter medium. Most fabric (cloth) and paper filters have pore sizes greater than the diameters of viruses and bacteria, so removal of these microbes is low, unless the microbes are associated with larger particles. However, some membrane and fiber filters have pore sizes small enough to efficiently remove parasites (one to several micrometers pore size), bacteria (0.1-1 micrometer pore size) and viruses (0.01 to 0.001 micrometer pore size or ultrafilters). Typically, such filters require advanced fabrication methods, special filter holders and the use of pressure to force the water through the filter media. For these reasons, such filters and their associated hardware are not readily available and their costs generally are too high for widespread use to treat household water in many regions and countries. However, simple fiber, fabric, paper and other filters and filter holders for them are available for widespread,

practical and affordable household treatment of collected and stored water throughout much of the world.

Some waterborne and water-associated pathogens are relatively large, such as the free-swimming larval forms (cercariae) of schistosomes and *Faciola* species, guinea worm larvae within their intermediate crustacean host (*Cyclops*), and bacterial pathogens associated with relatively large copepods and other zooplankters in water, such as the bacterium *Vibrio cholerae*. Various types of filters, including fabric and paper filters can physically remove these larger, free-living pathogens as well as the smaller ones associated with larger planktonic organisms. Paper filters have been recommended for the removal of schistosomes and polyester or monofilament nylon cloth filters have been recommended for the removal of the *Cyclops* vector of guinea worm (Imtiaz et al., 1990). Such filters have been used successfully at both the household and community levels (Aikhomu et al., 2000). Colwell and colleagues have shown that various types of sari cloth (fine mesh, woven cotton fabric) and nylon mesh can be used in single or multiple layers to remove from water the zooplankton and phytoplankton harboring *V. cholerae*, thereby reducing the *V. cholerae* concentrations by >95 to >99% (Huq et al., 1996). Where waterborne schistosomes, guinea worms, *Faciola* species and zooplankton-associated *V. cholerae* are a problem, use of these simple, point-of-use filter methods are recommended and encouraged, especially if other control measures are not available or difficult to implement.

However, typical fabric, paper, monofilament nylon and similar filters are not recommended for general treatment of household water. This is because the pore sizes of these filters are too large to appreciably retain viruses, bacteria and smaller protozoan parasites, especially if such microbes are free and not associated with large particles or organisms. Therefore, other types of physical or chemical water treatment processes are usually needed to effectively control a wider range of waterborne or water-associated microbial pathogens in household drinking water supplies. However, fabric, paper and similar filters can be used in conjunction with coagulation processes or disinfection processes to achieve improved reductions of particles (turbidity) and microbes in water. Such combined or multi-step systems are described elsewhere in this report. Furthermore, the World Health Organization and the international health community strongly support the use of filtration with fabric, paper and other mesh filter media as an essential intervention to eradicate guinea worm (dracunculiasis).

4.7 Porous ceramic filters

Porous ceramic filters made of clay, carved porous stone and other media have been used to filter water since ancient times and were cited by Aristotle (322-354 BCE). Modern accounts of ceramic filters for household use date back to at least the 18th century (Baker, 1948). Most modern ceramic filters are in the form of vessels or hollow cylindrical "candles". Water generally passes from the exterior of the candle to the inside, although some porous clay filters are designed to filter water from the inside to the outside. Many commercially produced ceramic filters are impregnated with silver to act as a bacteriostatic agent and prevent biofilm formation on the filter surface and excessive microbial levels in the product water. However, all porous ceramic media filters require regular cleaning to remove accumulated material and restore normal flow rate. Porous ceramic filters can be made in various pore sizes and most modern ceramic filters produced in the developed countries of the world are

rated to have micron or sub-micron pore sizes that efficiently remove bacteria as well as parasites. Many ceramic filters are composed of media capable of adsorbing viruses and in principle can achieve high virus removal efficiencies. However, because adsorption sites for viruses often become occupied by competing adsorbents, virus adsorption efficiency decreases with increased use and may become inefficient, unless physical or chemical cleaning procedures can restore the virus adsorption sites.

Porous ceramic filters are made of various mineral media, including various types of clays, diatomaceous earth, glass and other fine particles. The media are blended, shaped by manual or mechanical methods, dried and then fired at various temperatures to achieve different pore sizes and filtration properties. Some are unfired to maintain an open pore structure for filtration. Most ceramic filters are easy to use and are a potentially sustainable technology. The availability of suitable raw materials and the appropriate technology to blend these raw materials, shape the filter units and then perhaps fire them in a kiln are the main technical and accessibility barriers to their availability in developing countries. The need for inspection and other quality control measures, as well as appropriate testing for proper pore size are also important requirements for their production. Some units are brittle and fragile and therefore, can break during use. Broken filters, even if only slightly cracked, are unsuitable for removal of particles and microbial contaminants from water.

Ceramic filters for point-of-use water treatment are being produced and have come into widespread use in many parts of the world. Ceramic filters containing fired clay, limestone, lime and calcium sulfate have been produced for water filtration in Pakistan (Jaffar et al., 1990). These filters were found to reduce turbidity by 90% and bacteria by 60%. Ceramic filter candles that are 6 cm diameter and 11 cm long have been produced commercially in Cote d'Ivoire for less than US\$10 (Ceramiques d'Afrique) and other low cost ceramic filters are being produced in different parts of the developing world with the assistance of the organization Potters for Peace. The extent to which ceramic filters being produced in the developing world have been or are being tested for reductions of waterborne microbes such as viruses, bacteria and parasites and their waterborne diseases is uncertain at this time. Such performance evaluation for microbial reductions would be valuable information and provide a basis verifying the quality of the filters. Ceramic filters manufactured commercially in various countries of the developed world, such as the United Kingdom and the United States of America, have been extensively tested for efficacy in reducing various waterborne microbial contaminants and many are certified for their performance microbial characteristics. Some of these are rated to remove at least 99.9999% of bacteria, such as *Klebsiella terrigena*, 99.99% of viruses, such as polioviruses and rotaviruses, and 99.9% of *Giardia* cysts and *Cryptosporidium* oocysts as required for Point-of-Use Microbiological Water Purifiers in the United States (USEPA, 1987). These filters tend to be more costly than most of those produced in developing countries, and therefore, their accessibility, affordability and sustainability for household water treatment by the poorest people in developing countries is uncertain at this time.

Overall, ceramic filters are recommended for use in water treatment at the household level. The main barriers to the production, distribution and use of fired or unfired ceramic filter-adsorbers are the availability of trained workers, fabrication and distribution facilities and cost. Further efforts are needed to define and implement

appropriate manufacturing procedures and product performance characteristics of these filters in order to achieve products of acceptable quality that are capable of adequate microbe reductions from water. A simple and affordable method to test the quality and integrity of these filters also is recommended for use in situations where more technically demanding and costly testing is not available. . Quality and performance criteria and data for ceramic filters made in the developing world would provide a basis to judge quality and verify acceptable performance. However, the use of any intact ceramic filter to treat household water is likely to provide some improvement in water quality and therefore is preferable to no water treatment at all.

4.8 Diatomaceous earth filters

Diatomaceous earth (DE) and other fine granular media also can be used to remove particulates and microbial contaminants from water by so-called precoat and body feed filtration. Such filters have achieved high removal efficiencies of a wide range of waterborne microbial contaminants without chemical pre-treatment of the water (Cleasby, 1990; Logsdon, 1990). A thin layer or cake of the fine granular or powdery filter medium is precoat or deposited by filtration onto a permeable material held by a porous, rigid support to comprise a filter element. The water to be filtered often is supplemented with more filter medium as so-called body feed. As water passes through the filter, particulates are removed along with the body feed filter medium. This system maintains target flow rates while achieving high efficient particulate removal. DE filters also are capable of moderate to high pathogen removals (Logsdon, 1990). Eventually, the accumulation of impurities requires the removal of accumulated filter medium, cleaning of the filter medium support and reapplication of filter medium precoat to start the process over again. Although such DE and other precoat-body feed filter systems are used for small scale and point-of-use water treatment, they require a reliable, affordable source of filtration medium, regular care and maintenance, and they produce a spent, contaminated filter medium that may be difficult to dispose of properly. In addition, the filter media are difficult to handle when dry because as fine particles they pose a respiratory hazard. Because of these drawbacks, DE filters are not likely to be widely use for household water treatment in many parts of the world and in many settings, and therefore, they are not recommended for this purpose.

Table 11 Types, Performance Characteristics, Advantages and Disadvantages and Costs of Alternative Filters for Household Water Treatment

Filter Type	Advantages	Disadvantages	Comments
Rapid, Granular Media	See Table 8 above for details on these filters		
Slow Sand Filters	Useable on a small scale at community and maybe household level; relatively simple; can use local, low cost construction materials and filter media; relatively easy to operate manually; high turbidity and microbe reductions.	Requires some technical know-how for fabrication and use; initial education and training needed; requires user maintenance to clean and operate (materials, skill, labor and time).	Simple, affordable and appropriate technology at the community level; less appropriate for treating individual household water, unless by a collection of households.
Fiber, fabric and membrane filters	Usable at household level if filter media is available, easy to use and affordable	Wide range of filter media, pore sizes and formats; microbe removal varies with filter media; best used to remove large and particle-associated microbes; not practical, available or affordable for efficient removal of all waterborne pathogens	Has been effective in reducing guinea worm, <i>Fasciola</i> and schistosomiasis; can be coupled with other treatment methods (coagulation and disinfection) to improve overall microbe reductions
Porous ceramic filters	Simple and effective	Quality ceramic filters may not be	Greater efforts are needed to

	technology for use at the household level; extensive microbe reductions by quality filters; filters can be locally made from local materials, if education and training provided	available or affordable in some Quality of local made filters may be difficult to document unless testing is available to verify microbe reductions; need criteria and systems to assure quality and performance of filters	promote the development of effective ceramic filters for household water treatment in developing countries by adapting the local production of clay and other ceramic ware now used for other purposes to water treatment
Diatomaceous earth filters	Efficient (moderate to high) removals of waterborne pathogens	Not practical for household use; need specialized materials, construction and operations including regular maintenance; dry media a respiratory hazard	Pre-fabricated, commercial DE filters and media are available in some countries but high costs and low availability may limit household use in other places

4.9 Aeration

Aeration of water alone is simple, practical, and affordable, especially if done manually in a bottle or other vessel. Aeration of water has been practiced since ancient times and was believed to improve water quality by "sweetening" and "softening" it (Baker, 1948). It was later discovered that aeration indeed oxygenated anaerobic waters and that such a process would oxidize and precipitate reduced iron, manganese and sulfur, as well as strip volatile organic compounds, some taste and odor compounds, and radon. However, there is no evidence that aeration for brief time periods (minutes) has a direct microbiocidal effect. However, aeration of water introduces oxygen, which can cause chemical reactions, such as precipitation in anaerobic water containing certain dissolved solutes, and which can contribute indirectly to other process that may lead to microbial reductions. In addition, studies suggest that aeration has a synergistic effect with sunlight and heat on disinfection by solar radiation of water held in clear bottles. The mechanisms of this effect are not fully understood. However, they may involve conversion of molecular oxygen to more microbiocidal chemical species by photooxidation reactions with microbial components or other constituents in the water, leading to photodynamic inactivation. Further studies of the ability of aeration to inactivate microbes in water either alone or in combination with other agents needs further study. Currently, there is no clear evidence that aeration alone is capable of appreciably and consistently reducing microbes in water.

5. Chemical Methods of Water Treatment

A number of chemical methods are used for water treatment at point-of-use or entry and for community water systems. These methods can be grouped into several main categories with respect to their purpose and the nature of the technology. The main categories to consider here are: (1) chemical pre-treatments by coagulation-flocculation or precipitation prior to sedimentation or filtration, (2) adsorption process, (3) ion exchange processes and (4) chemical disinfection processes. All of these processes can contribute to microbial reductions from water, but the chemical disinfection processes are specifically intended to inactivate pathogens and other microbes in water. Therefore, chemical disinfection processes appropriate for household water treatment in the developing world will be the focus of attention in this section of the report. Other chemical methods for water treatment will be examined for their efficacy in microbial reductions and their applicability to household water treatment.

5.1 Chemical coagulation, flocculation and precipitation

5.1.1 Introduction

Chemical precipitation or coagulation and flocculation with various salts of aluminum (e.g., alum), iron, lime and other inorganic or organic chemicals are widely used processes to treat water for the removal of colloidal particles (turbidity) and microbes. Treatment of water by the addition of chemical coagulants and precipitants has been practiced since ancient times, even though the principles and physico-chemical mechanisms may not have been understood. Sanskrit writings refer to the use of vegetable substances, such as the seed contents of *Strychnos potatorum* and *Moringa oleifera*, which are still in use today for household water treatment (Gupta and Chaudhuri, 1992). Judeo-Christian, Greek and Roman records document adding "salt", lime, "aluminous earth", pulverized barley, polenta as precipitants to purify water. Although alum and iron salts are the most widely used chemical coagulants for community drinking water treatment, other coagulants have been and are being used to coagulate household water at point of use, including alum potash, crushed almonds or beans and the contents of *Moringa* and *Strychnos* seeds. Table 12 lists some the coagulants that have been and are being used for water treatment at the community and household level, their advantages and disadvantages and their costs.

Table 12. Chemical Coagulants for Water Treatment and their Advantages, Disadvantage and Costs for Household Use

Coagulant	Community/Ho usehold Use	Advantages	Disadvantages	Cost*	Comments
Alum (aluminum sulfate, etc.), alum potash	Yes/rare-moderate	Community use common; simple technology	Difficult to optimize without training and equipment	Mod- erate?	Proper use requires skill
Iron salts (ferric chloride or sulfate)	Yes/rare	Same as Alum	Same as Alum	Mod- erate?	Proper use requires skill
Lime (Ca(OH ₂)), lime+soda ash (Na ₂ CO ₃), caustic soda (NaOH)	Yes/rare-moderate	Same as Alum	Same as Alum; pH control and neutralization a problem; hazardous chemicals	Mod- erate to high?	Softeners; not applicable to many waters
Soluble synthetic organic polymers	Yes/no-rare	Improve coagulation with alum and iron salts	Same as Alum; hard to dose; need training & equipment; hazardous chemicals	High	Use with other coagulants; limited availability
Natural polymers (carbohydrates) from seeds, nuts, beans, etc.	Rare/Yes (in some developing countries)	Effective, available and culturally accepted in some places	Source plant required; training and skill required; cultural acceptability; may be toxic	Low	Traditional use based on historical practices

*Estimated Annual Cost: low is <US\$0.001 per liter, moderate is 0.001-0.01\$ per liter and high is >0.01 per liter (corresponds to about <US\$10, \$10-100 and >\$100, respectively, assuming household use of about 25 liter per day)

Chemical coagulation-flocculation enhances the removal of colloidal particles by destabilizing them, chemically precipitating them and accumulating the precipitated material into larger "floc" particles that can be removed by gravity settling or filtering. Flocculation causes aggregation into even larger floc particles that enhances removal by gravity settling or filtration. Coagulation with aluminum or iron salts results in the

formation of insoluble, positively charged aluminum or iron hydroxide (or polymeric aluminum- or iron-hydroxo complexes) that efficiently attracts negatively charged colloidal particles, including microbes. Coagulation-flocculation or precipitation using lime, lime soda ash and caustic soda is used to "soften" water, usually ground water, by removing (precipitating) calcium, magnesium, iron, manganese and other polyvalent, metallic cations that contribute to hardness. However, reductions in microbial contaminants as well as turbidity, and dissolved and colloidal organic matter are also achieved in this process.

5.1.2 Microbial reductions by coagulation-flocculation

Optimum coagulation to achieve maximum reductions of turbidity and microbes requires careful control of coagulant dose, pH and consideration of the quality of the water being treated, as well as appropriate mixing conditions for optimum flocculation. Lack of attention to these details can result in poor coagulation-flocculation and inefficient removal of particles and microbes. Under optimum conditions, coagulation-flocculation and sedimentation with alum and iron can achieve microbial reductions of >90 to >99% for all classes of waterborne pathogens (Sproul, 1974, Leong, 1982, Payment and Armon, 1989). However, poor microbial reductions occur (<90%) when coagulation-flocculation or precipitation conditions are sub-optimal (Ongerth, 1990). Even greater microbial reductions (>99.99%) can be achieved with lime coagulation-flocculation or precipitation if high pH levels are achieved in the process (pH >11) to cause microbial inactivation as well as physical removal.

5.1.3 Alum and iron coagulation

Because coagulation-flocculation treatment with alum, iron and other coagulants requires knowledge, skills to optimize treatment conditions, it is generally considered to be beyond the reach of most consumers. Most authorities consider such treatment to be best performed in specialized central facilities by trained personnel. This type of treatment is less likely to be performed reliably at point-of-use for household water treatment. Furthermore, the limited availability and relatively high costs of alum and ferric salts in some places present additional obstacles to widespread implementation of this technology at the household level.

Despite the caveats and limitations, alum coagulation and precipitation to remove turbidity and other visible contaminants from water at the household level has been traditionally practiced for centuries in many parts of the world (Jahn and Dirar, 1979; Gupta and Chaudhuri, 1992). When potash alum was evaluated for household water treatment in a suburban community in Myanmar by adding it to water in traditional storage vessels (160L capacity) at 500 mg/L, fecal coliform contamination was reduced by 90-98% and consumer acceptance of the treated water was high (Oo et al., 1993). The ability of the intervention to reduce diarrheal disease was not reported. In another study, alum potash was added to household water stored in pitchers of families with an index case of cholera and intervention and control (no alum potash) households were visited to 10 successive days to track cases of enteric illness (Khan et al., 1984). Illness among family members was significantly lower ($p < 0.05$) in intervention households (9.6%) than in control households (17.7%). The authors concluded that household water treatment by adding a pinch of alum potash was

effective in reducing cholera transmission during outbreaks and was an appropriate and low cost (1 cent per 20 liters) intervention.

5.1.4 Seed extract coagulation-flocculation

Coagulation-flocculation with extracts from natural and renewable vegetation has been widely practiced since recorded time, and appears to be an effective and accepted physical-chemical treatment for household water in some parts of the world. In particular, extracts from the seeds of *Moringa* species, the trees of which are widely present in Africa, the Middle East and the Indian subcontinent, have the potential to be an effective, simple and low-cost coagulant-flocculent of turbid surface water than can be implemented for household water treatment (Jahn and Dirar, 1979; Jahn, 1981; Jahn, 1988; Olsen, 1987). The effectiveness of another traditional seed or nut extract, from the *nirmali* plant or *Strychnos potatorum* (also called the clearing nut) to coagulate-flocculate or precipitate microbes and turbidity in water also has been determined (Tripathi et al., 1976; Able et al, 1984). Microbial reductions of about 50% and 95% have been reported for plate count bacteria and turbidity, respectively. Despite the potential usefulness of *Moringa oleifera*, *Strychnos potatorum* and other seed extracts for treatment of turbid water, there has been little effort to characterize the active agents in these seed extracts or evaluate the efficacy as coagulants in reducing microbes from waters having different turbidities. The chemical composition of the coagulant in *Strychnos potatorum* has been identified as a polysaccharide consisting of a 1:7 mixture of galactomannan and galactan. These findings suggest that such seed extracts may function as a particulate, colloidal and soluble polymeric coagulant as well as a coagulant aid. The presence of other constituents in these seed extracts are uncertain, and there is concern that they may contain toxicants, because the portions of the plant also are used for medicinal purposes. Also, little has been done define, optimize and standardize conditions for their use. Furthermore, there appears to be little current effort to encourage or disseminate such treatment for household water or determine its acceptability, sustainability, costs and effectiveness in reducing waterborne infectious disease.

5.1.5 Summary

The results of several studies suggest that alum and other coagulation-flocculation or chemical precipitation methods can be applied at the household level to improve the microbiological quality of water and reduce waterborne transmission of diarrheal disease in developing countries. However, further studies are needed to determine if this type of treatment can be effectively, safely, and affordably applied for household water at point of use by the diverse populations living in a variety of settings. Furthermore, it is uncertain if household use of coagulation-flocculation can be optimized to provide efficient and consistent microbial reductions on a sustainable basis. Therefore, household water treatment by coagulation-flocculation and precipitation is not be widely recommended at this time. More information is needed on the effectiveness, reliability, availability, sustainability and affordability of these processes when applied at the household level. However, newer approaches to treatment of collected and stored household water have combined chemical coagulation-flocculation with chemical disinfection to achieve both efficient physical removal as well as inactivation of waterborne microbes. These systems offer great promise as effective, simple and affordable household water treatment technologies. These systems and their performance are described in a later section of this report.

5.2 Adsorption processes

5.2.1 Introduction

Adsorption processes and adsorbents such as charcoal, clay, glass and various types of organic matter have been used for water treatment since ancient times. Some of these adsorption processes tend to overlap with either filtration processes, because the media are often used in the form of a filter through which water is passed, or coagulation processes, because they may be combined with chemical coagulants. Therefore, adsorption processes can be carried out concurrently with filtration or coagulation. The candidate media potentially used for adsorption treatment of household water are shown in Table 13.

Table 13. Adsorbents for Water Treatment and their Advantages, Disadvantages and Costs for Household Use

Adsorbent	Community/ Household Use	Advantages	Disadvantages	Cost*	Comments
Clays	Rare/rare-moderate	Some efficiently adsorb microbes; adaptable to many treatment formats	Some adsorb microbes poorly; availability limited	Low to moderate	Use as an adsorbent or coagulant
Charcoal (C), Activated Carbon (AC)	Moderate/Moderate; (AC more in developed world; C more in developing world)	Adaptable to many treatment formats; charcoal often readily available	Poor microbe adsorption; can degrade microbial quality	Moderate (C) to high (AC)	Used as adsorbents or coagulants; use varies regionally; C use based on traditional practice
Crushed organic matter: seeds, rice, etc.	No-very rare/Rare-moderate in some countries	Ditto charcoal and carbon	Poor microbe adsorption; can degrade microbial quality	Low	Used as adsorbent or coagulant

*See footnote to Table 11 for explanation of cost basis.

5.2.2 Clay adsorption

Clay continues to be used as an adsorption medium for household water treatment in some regions and countries, with applications as clay particles in suspension, as filters (usually fired ceramic) or in conjunction with a chemical coagulant. Porous, fired ceramic clay filters (and adsorbers), typically as candles or other vessels have been described in a previous section of this report. The use of clay in conjunction with chemical coagulants also has been described elsewhere (Lund and Nissen, 1986; Olsen, 1987). When used alone, clays can decrease turbidity and microbes in water by about 90-95%. However, some microbes may not efficiently or consistently adsorb to certain, which reduces the overall efficiency of clay adsorption as a household water treatment process. Furthermore, the use of clay particles as suspensions in water is limited by the availability of the material and by the need to control the process so that the particles will settle, either alone or in the presence of a coagulant or coagulant aid. The use of such technology for clay adsorption requires training and is best supported by specialized equipment to carry out and monitor

treatment effectiveness. Therefore, clay adsorption is not well suited for household water treatment.

5.2.3 Charcoal and activated carbon adsorption

Charcoal and activated carbon have been used extensively as adsorbents for water treatment in the developed and developing world. The main application is the reduction of toxic organic compounds as well as objectionable taste and odor compounds in the water. In developed countries granular or powdered activated carbon are used in community water treatment and granular or pressed carbon block is typically used for point-of-use or household water treatment (AWWA, 1999; LeChevallier and McFeters, 1990). Although fresh or virgin charcoal or activated carbon will adsorb microbes, including pathogens, from water, dissolved organic matter in the water rapidly takes up adsorption sites and the carbon rapidly develops a biofilm. Therefore, carbon is not likely to appreciably reduce pathogenic enteric microbes in water over an extended period of time. If anything, carbon particles are prone to shedding heterotrophic plate count bacteria and other colonizing microbes into the product water, thereby reducing the microbial quality. In many point-of-use devices the carbon is impregnated or commingled with silver that serves as a bacteriostatic agent to reduce microbial colonization and control microbial proliferation in the product water. Fecal indicator bacteria, such as total and fecal coliforms, and opportunistic bacterial pathogens, such as *Aeromonas* species are capable of colonizing carbon particles and appearing in product water. For these reasons, activated carbon is not recommended as a treatment method to reduce pathogenic microbes in drinking water. Additional treatment, such as chemical disinfection, often is needed to reduce microbe levels in carbon-treated water. Mixed media containing carbon along with chemical agents effective in microbial retention have been developed and evaluated. For example, carbon filters containing aluminum or iron precipitates have been described, and these filters have achieved appreciable microbial reduction in laboratory scale tests (Farrah et al., 2000). Therefore, it is possible that granular activated carbon filter media prepared with chemical agents more effective in retaining microbes may eventually become more widely available for point-of-use treatment of household water. However, the conventional charcoal and activated carbon media currently available for water treatment are not recommended for use at the household level to reduce microbial contaminants. Only charcoal or activated carbon media that been combined with other materials to improve microbial reductions should be considered for household treatment of collected and stores water and then only if there are performance data or certifications to verify effective microbial reductions.

5.2.4 Vegetative matter adsorbents

Historically, other vegetative matter has been used as an adsorbent for water treatment, as has been previously noted (Baker, 1948). Of these other plant media, burnt rice hulls seems to have been the most widely used in recent times (Argawal and Kimondo, 1981; Barnes and Mampitiyarachichi, 1983). The application of this material has been in the form of a granular medium filter, either alone or in conjunction with another filter medium, such as sand or activated (burnt) coconut shell. Use of this water treatment medium is still limited, primarily to those parts of the world where rice agriculture is widely practiced and where other filter media are not readily available at low cost. However, these adsorbent materials and their

technologies require further development, evaluation and dissemination before they can be recommended for household water treatment in other parts of the world.

5.3 Ion exchange processes

5.3.1 Introduction

Ion exchange processes in water treatment have been used primarily for softening (hardness removal) in both community and point-of-use treatment and for disinfection in point-of-use treatment. Some ion exchange resins are used to deionize, disinfect or scavenge macromolecules from water. The main classes of ion exchangers used in water treatment and their advantages, disadvantages and costs are summarized in Table 14.

Table 14. Ion Exchangers and their Advantages, Disadvantages and their Advantages and Disadvantages for Household Use

Exchange Resin	Community/ Household Use	Advantages	Disadvantages	Cost*	Comments
Softening resins	Yes/Yes	Easy to use	Do not inactivate microbes; spent resin replacement and disposal required; unavailable in some parts of the world	High	Lack of microbial reduction makes them unsuitable for microbial reductions in household water treatment
Deionizing Resins	Yes/Yes	Inactivate microbes; easy to use	Not recommended for drinking water; spent resin replacement and disposal required; unavailable in some parts of the world	High	The effects on long-term consumption of deionised water on health are not fully understood.
Iodine Disinfection (tri-iodide and penta-iodide)	No/Yes	Inactivates microbes; easy to use	Risk of soluble iodine leaching into water; spent resin replacement and disposal required; unavailable in some parts of the world	High	Difficult to determine useable life without added technology; impractical and limited availability in developing world
Adsorbent and scavenging resins	No/Yes	Easy to use	Not likely to inactivate microbes; microbial colonization and release a concern; not available in some parts of the world	High	Difficult to determine useable life without added technology; impractical and limited availability in many parts of the world

*See Table 11 footnote for explanation of cost basis

5.3.2 Softening, deionizing and scavenging resins

Ion exchange typically employs synthetic polymeric resins that must be centrally manufactured in specialized production facilities. The costs of these synthetic resins are relatively high and their availability in developing countries is limited. Ion exchange using natural zeolites has been applied to softening, chemical adsorption

and other purposes in water treatment. However, natural zeolites have only limited availability worldwide, they require mining and processing systems that may be beyond the capacity of developing countries, and they have not been widely evaluated or used for microbial reductions in drinking water. The effects on long-term consumption of deionised water on health are not fully understood.

Water softening resins are intended to remove hardness and they do not remove or inactivate waterborne microbes on a sustained basis. Furthermore, softening resins often become colonized with bacteria, resulting in excessive bacterial levels in product water, and they also increase the levels of sodium in the product water. In developed countries, point-of-use water treatment systems employing softening or scavenging resins often include additional treatment methods to reduce microbial loads in product water. Softening resins are relatively expensive, require regular monitoring and frequent replacement or recharging (regeneration of exchange capacity of spent resin); therefore, they are not practical for widespread household use to treat collected stored water. Because of their inability to reduce microbes, their complexities and other limitations, as described in Table 14, softening and scavenging resins are not recommended for household water treatment.

5.3.3 Ion exchange disinfection

Ion exchange disinfection is primarily with iodine in the form of tri-iodide or penta-iodide exchange resins. Portable and point-of-use iodine exchange resins have been developed and extensively evaluated for inactivation of waterborne pathogens, primarily in developed countries. Most of these are in the form of pour through cups, pitchers, columns or other configurations through which water is passed so that microbes come in contact with the iodine on the resin. Point-of-use iodine resins have been found to extensively inactivate viruses, bacteria and protozoan parasites (Marchin et al., 1983; 1985; Naranjo et al., 1997; Upton et al., 1988). While such iodine exchange disinfection resins are both effective and convenient, they are too expensive to be used by the world's poorest people and the production and availability of these resins is limited primarily to some developed countries. As described in the next section of this report, other chemical disinfection methods besides ion exchange halogen resins are available and preferred for household treatment to inactivate microbes in collected and stored drinking water.

5.4 Chemical Disinfection Processes

5.4.1 Chemical disinfectants for drinking water

Chemical disinfection is considered the essential and most direct treatment to inactivate or destroy pathogenic and other microbes in drinking water. The abilities of chemical disinfectants to inactivate waterborne microbes and reduce waterborne infectious disease transmission have been well known since the germ theory was validated in the mid-19th century. However, it was not until the late 19th and early 20th centuries that chlorine became widely recognized as an effective, practical and affordable disinfectant of drinking water. Subsequently, ozone and chlorine dioxide were developed as drinking water disinfectants and their ability to inactivate waterborne pathogens was determined.

Today, chemical disinfection of drinking water is widely recognized as safe and effective and is promoted and practiced at the community level as well as at point-of-

use. The preferred and most widely used chemical disinfectants of drinking water are all relatively strong oxidants, namely free chlorine, ozone, chlorine dioxide, chloramines (primarily monochloramine), and oxidants generated by electrolysis of sodium chloride solution (primarily or exclusively free chlorine). Additional chemical disinfectants sometimes used for drinking water are acids and bases; these agents inactivate microbes by creating either low or high pH levels in the water, respectively. The combined use of multiple treatment processes or "barriers" is a widely embraced principle in drinking water science and technology that is widely applied in community drinking water supplies, especially for surface waters. This approach also has been adapted to water treatment at the household level by the use of combined chemical treatments that are designed to chemically coagulate, flocculate, filter and disinfect the water. The advantages, disadvantages, costs and practicalities of these disinfectants for household treatment at the household levels are summarized in Table 15.

Table 15. Chemical Disinfectants for Drinking Water Supplies: Advantages, Disadvantages and Costs for Household Use

Disinfectant	Community/Household Use	Advantages	Disadvantages	Cost*	Comments
Free chlorine (NaOCl, Ca(OCl) ₂)	Yes/Yes (worldwide, but not in some regions)	Easy to use; effective against most pathogens; stable residual	Not available worldwide; some users object to taste and odor	Low	The most widely used drinking water disinfectant; proven technology
Electro-chemically generated oxidant from NaCl	Yes/Yes (limited distribution)	Easy to use; effective against most pathogens; stable residual	Not available worldwide; some users object to taste and odor (mostly chlorine)	Low	Practical for worldwide use; can generate on site by electrolysis of NaCl; proven technology
Chloramines (monochloramine)	Yes/Rare (less widely used than free chlorine; must react free chlorine with ammonia)	Stable residual	Less effective microbicide than free chlorine; requires skill and equipment to generate on-site; household use impractical	Moderate	More difficult to use than free chlorine; potentially available where free chlorine is used but requires ammonia source
Ozone	Yes/Rare (less widely than free chlorine; mostly in Europe)	Highly microbicidal;	No residual; Generate onsite; hard to use; need special facilities and trained personnel; hazardous	High	Not practical for household use in many regions and countries
Chlorine Dioxide	Yes/Rare (much less use than free chlorine; for individual use by acidifying chlorite or chlorate)	Highly microbicidal	Poor residual; generate on-site; some technologies require special facilities, trained personnel and are hazardous; toxicologic concerns	High	Can be generated on-site by reacting chlorate or chlorite salts with acids; reactants may not be available and some are hazardous
Acids (especially lime juice and mineral acids) and hydroxide (caustic)	Limited/Limited (in community systems mineral acid and base for pH control; lime (CaO) and soda ash for chemical softening; in household)	Acids inactivate <i>V. cholerae</i> & some other bacteria; limes and chemicals widely available	Limited microbicidal activity; CaO use requires special facilities and trained personnel and is hazardous; CaO process difficult to control	High for CaO; low-moderate for lime juice	Lime juice has been reported to be effective for cholera control at the household level; Chemical acids and lime precipitation not practical for household use

	Treatment lime juice for inactivation of <i>V. cholerae</i>				
Combined chlorination, coagulation-flocculation-filtration systems	Yes/Yes As sequential processes in community systems and as combined processes in household systems	Highly effective for microbe reductions	Availability now limited; requires some training and skill; efficacy varies with water quality;	High	Limited availability and higher cost (compared to chlorine) are barriers to household use in some countries and regions

*See Table 11 footnote for explanation of cost basis.

Iodine, silver, copper, quaternary ammonium compounds and some other chemical agents have been proposed and are sometimes used to inactivate waterborne pathogens. However, none of them are considered suitable for long-term use to disinfect drinking water for various important and valid reasons. Iodine is difficult to deliver to water and can cause adverse health effects, silver and copper are difficult to deliver to water and primarily only bacteriostatic, and quaternary ammonium compounds are limited in availability, costly and not effective against viruses and parasites. However, iodine, either dissolved in water or in the form of an iodinated exchange resin, has been used for short-term water treatment by outdoor recreationists (campers, hikers, etc), field military personnel, and persons displaced by natural disasters and human conflicts (wars and other societal disruptions). Silver is used as a bacteriostatic agent for point-of-use or household water treatment by storing water in vessels composed of silver or passing water through porous or granular filter media impregnated with silver. However, the extent to which silver alone inactivates microbes in water is limited, bacteria may develop silver resistance and many microbes, such as viruses, protozoan cysts and oocysts and bacterial spores, are not inactivated at silver concentrations employed for point-of-use drinking water treatment. Therefore, these agents are not recommended for routine disinfection of household water.

5.4.2 Factors influencing disinfection efficacy

The ability to inactivate waterborne microbes differs among the commonly used disinfectants as follows (from most to least potent): ozone > chlorine dioxide \$ electrochemically generated oxidant \$ free chlorine > chloramines. It is also noteworthy that these disinfectants differ in their stability and ability to persist in water to maintain a disinfectant residual. Ozone is a gas and the least stable in water; it is unable to provide a stable disinfectant residual. Chlorine dioxide is a dissolved gas in water and capable of persisting typically for periods of hours. Free chlorine is stable in water and can persist for days if there is no appreciable chlorine demanding material in the water. Because electrochemically generated oxidant from NaCl is primarily free chlorine (about 80 to nearly 100%, depending on the electrolysis conditions), it is relatively stable in water. Chloramines (primarily monochloramine) are the most stable of the listed disinfectants in water and can persist for many days.

Waterborne microbes also differ in their resistance to the chemical disinfectants used for drinking water as follows (from greatest to least resistant): parasites (protozoan cysts and oocysts and helminth ova) \$ bacterial spores \$ acid-fast bacteria (notably the *Mycobacteria*) > enteric viruses > vegetative bacteria. Within each of these major

microbe groups there are differences in the resistance of different sub-groups and specific species or strains of microbes. In addition, the resistance of waterborne microbes to inactivation by chemical disinfectants is influenced by their physical and physiological states. Microbes in the form of aggregates (clumps) or embedded within other matrices (membrane, biofilm, another cell, or fecal matter, for example) are protected from being reached by chemical disinfectants and by the oxidant demand of the material in which they are present. This makes the microbes more resistant to inactivation.

The quality of the water to be disinfected also influences microbial inactivation by chemical disinfectants. Particulate, colloidal and dissolved constituents in water can protect microbes from inactivation by reacting with and consuming the chemical disinfectant. The microbiocidal activity of some chemical disinfectants is influenced by the pH of the water, with generally better inactivation at low pH than at high pH for free chlorine, for example. Further details of the water quality factors influencing microbial inactivation are presented in detail elsewhere (Sobsey, 1989).

5.4.3 Free chlorine treatment

Of the drinking water disinfectants, free chlorine is the most widely used, the most easily used and the most affordable. It is also highly effective against nearly all waterborne pathogens, with notable exceptions being *Cryptosporidium parvum* oocysts and *Mycobacteria* species (Sobsey, 1989). At doses of a few mg/l and contact times of about 30 minutes, free chlorine generally inactivates $>4 \log_{10}$ ($>99.99\%$) of enteric bacteria and viruses. For point-of-use or household water treatment, the most practical forms of free chlorine are liquid sodium hypochlorite, solid calcium hypochlorite and bleaching powder (chloride of lime; a mixture of calcium hydroxide, calcium chloride and calcium hypochlorite). Bleaching powder is less desirable as a drinking water disinfectant because it may contain other additives that are undesirable in drinking water (detergents, fragrances, abrasives, etc). and because it is somewhat unstable, especially if exposed to the atmosphere or to water.

In addition to the well-documented evidence that free chlorine effectively inactivates waterborne microbes and greatly reduces the risks of waterborne disease in community water supplies, there is considerable evidence of the same beneficial effects in point-of-use and household water supplies. Table 16 summarizes the results of carefully designed intervention studies documenting the ability of free chlorine to reduce microbes and to reduce household diarrheal disease when used to disinfect household drinking water in developing countries. The results of these studies show conclusively that chlorination and storage of water in either a "safe" (specially designed) vessel or even a traditional vessel reduces diarrheal disease by about 20-48% and significantly improves the microbial quality of water (by reducing thermotolerant (or fecal) coliforms, *E. coli*, *V. cholerae* and other microbial contaminants). Most of the recent studies on chlorination of household water have been done by the US Centers for Disease Control and Prevention (CDC) and its many partners and collaborators around the world (CDC, 2001). The CDC intervention includes a hygiene education component and the use of a plastic, narrow-mouth water storage vessel with a spigot designed to minimize post-treatment contamination. Therefore, the beneficial effects of this chlorination system in the form of improved microbial quality and reduced diarrheal and other infectious diseases may also include the positive effects of the improved storage vessel as well as improved hygienic

practices. However, some water chlorination studies listed in Table 16 tested only the effect of chlorination or chlorination plus the use of an improved water storage vessel for better protection of the chlorinated water during storage. These studies of the water intervention only also demonstrate improved microbiological quality of chlorinated water and reduced diarrheal and other infectious diseases.

Table 16. Efficacy of Chlorination and Storage in a Specialized Container (Safewater System) to Disinfect Household Water: Disease Reduction and Improvement in Microbial Quality

Loca-Tion	Water and Service Level ^a	Treatment	Storage Vessel	Disease Reduc-tion (%)	Significant Microbe Decrease? ^b	Inter-ven-tion ^c	Reference
Saudi Arabia	House-hold/ On, G	Free Chlorine	House-hold Tanks - Outside	48%, diarrhea	Yes, <i>E. coli</i> +ive \ from 100 to 3%	W	Mhafouz et al, 1995
India	House-hold;	Free Chlorine	Earthen-ware	17-7.3%, cholera	Not Measured	W	Deb et al., 1986
Bolivia	House-hold/ On, G	Electro-chemical Oxidant (Mostly Free Chlorine)	Special Vessel ^d	44%, diarrhea	Yes, <i>E. coli</i> +ive \ from 94 to 22%; Median <i>E. coli</i> \ from >20,000 to 0	W + SH	Quick et al., 1999
Bangla-desh	House-hold/ Off, M	Free Chlorine	Improved Vessel ^e	20.8%, diarrhea	Yes,	W	Handzel, 1998
Guinea-Bisseau	ORS ^f / Off/G or S not reported	Free Chlorine	Special Vessel ^d	No Data	Yes, mean <i>E. coli</i> \ from 6200 to 0/100 ml	W + SH	Daniels et al., 1999
Guate-mala	Street-vended Water/ Off, M	Free Chlorine	Special Vessel ^d	No Data	Yes, <i>E. coli</i> +ive \ from >40 to <10%	W + SH	Sobel et al., 1998
Zambia	House-hold/Off or On not reported/G	Free Chlorine	Special ^d or Local Vessel	48%, diarrhea	Yes, <i>E. coli</i> +ive \ from 95+ to 31%	W + SH	Quick et al., in press
Mada-Gascar	House-hold	Free Chlorine; (traditional vessel)/Off, G or S not reported	Special ^d and Tradi-tional Vessels	90%, cholera, (during outbreak)	Yes, Median <i>E. coli</i> \ from 13 to 0/100 ml	W + SH	Mong et al. 2001 and Quick, pers. commun.
Uzbek-istan	House-hold/On and Off/M	Free Chlorine	Special ^g Vessel	85%, diarrhea	No (but based on small number of samples)	W	Semenza et al., 1998
Pakis-tan	House-hold/On and Off/ munici-pal	Free Chlorine	Special ^d Vessel	No Data	Yes, Thermotol. Colif. \ by 99.8%	W + SH	Luby et al., 2001

^aWater storage and source:

^bSignificant difference in disease burden in intervention household members than in control household members. In some cases only certain age groups were studied or scored for an effect.

^cW = Water intervention only. SH = Sanitation and health intervention.

^cWater and Service Level: Household stored water or other water; water service levels: on-plot (On) or off-plot (Off), communal (C), yard (Y), surface water (S), ground water (G), other water (O), mixed sources (M)

^dCDC vessel: Plastic (high-density polyethylene), about 20-L capacity, valved spigot to dispense water, 6-9 cm opening to fill and clean, handle to carry and re-position.

^e 12-L jerry can: plastic, 12-L capacity, medium opening for filling, cleaning and dispensing water.

^fORS = Oral rehydration solution.

^gNarrow-necked vessel with a spout

Only a few studies have not demonstrated the ability of household water chlorination to reduce diarrheal illness. One such study compared microbial water quality and diarrheal illness in households chlorinating drinking water stored in clay pots at a dose of 6.3 mg/l versus matched control households not chlorinating in rural village in Northeastern Brazil (Kirchhoff et al., 1984). Bacterial contamination of water in households chlorinating was significantly lower than in non-intervention households (70 versus 16,000 colonies per 100 ml, $p < 0.001$). However, diarrhea rates were not significantly different between the intervention and control households. Several factors may account for the lack of differences in diarrheal illness rates between the two sets of households. First, it is unclear whether or not the treated water was actually used for drinking purposes and at what consumption level. Second, the drinking water for all families was heavily contaminated pond water, so it may have continued to harbor appreciable levels of pathogens despite chlorination. Third, chlorine dose was not rigorously controlled and chlorine residual in stored household water was not measured. Incorrect chlorine dosing may have resulted in either too little chlorine to reduce pathogens or too much chlorine that caused families to stop using the water or drop out of the study. Eight of 9 families who dropped out of the study reported objectionable taste as the reason for dropping out. Additionally, families were not involved in the intervention process; they were passive recipients of it and received no hygiene education. Finally, because overall sanitary conditions were poor and socio-economic status was very low, a single intervention only on drinking water may not have had sufficient impact on overall pathogen exposure to observe a significant decrease in diarrheal illness, especially in a short-term study of only 18 weeks.

As summarized in Table 16, many studies have shown that the microbiological quality of stored household water can be significantly improved and diarrheal disease can be significantly reduced by adding chlorine to water stored in a household vessel. Recent studies have attempted to overcome the limitations and uncertainties of previous efforts by employing uniform and fully articulated systems of chlorine production, distribution and dosing, an improved, standardized household water storage container, and the inclusion of participatory education, motivation and behavior modification components (Mintz et al., 2001; USA CDC, 2000). A simple and low cost system of adding chlorine to collected household water stored in a dedicated, narrow-mouth plastic container (preferably with a valved spigot) has typically reduced waterborne microbes by >99% and reduced community diarrheal disease, including cholera, by as much as 17-90% (Handzel, 1998; Mintz et al., 1995; 2001; Quick et al., 1999; Semenza et al., 1998). To make the system sustainable efforts are made to have users purchase concentrated sodium hypochlorite that is produced in the community by electrolysis of NaCl solution. The concentrated sodium hypochlorite solution is added to household water stored in a specially designed,

rectangular, 20-liter plastic vessel with a moderate diameter, screw cap opening for filling and cleaning and a separate valved spigot to dispense the treated, stored water. The treatment and storage technology is accompanied and supported by an education, motivation (through social marketing) and behavior modification system to achieve community and household participation and improve hygiene behaviors related to household water use. This approach to providing microbially safe household drinking water, called the "CDC Safewater" system, has been successfully implemented in numerous communities, countries and regions in different parts of the world, including Latin America (Bolivia, Ecuador, Nicaragua and Peru), Central Asia (Uzbekistan), the Indian subcontinent (Pakistan), and Africa (Zambia and Madagascar) (Luby et al., 2001; May and Quick, 1998; Mong et al., 2001; Quick, et al. 1996; 1999; Semenza et al., 1998). In addition, similar systems have been used to disinfect water for oral rehydration therapy (ORT) solutions and for water and beverages marketed by street food vendors (Sobel et al., 1998; Daniels et al., 1999).

Consumer education, participation and social marketing are considered essential and integral to achieving acceptance and sustainability for this and other household drinking water treatment systems (Thevos et al., 2000). In addition, pilot and feasibility studies are also encouraged, as is economic, social and political support from donor agencies, NGOs, government agencies, the private sector and other sources. Such activities are recognized as essential for designing, mobilizing for, implementing and assessing this and other water quality management systems at the household level. Further considerations of the role of these factors in household water treatment systems are discussed in a later section of this report.

5.4.4 Chloramine treatment

Disinfection of water with chloramines or ammonia-chlorine is widely practiced in community water supplies in order to provide a long-lasting disinfectant residual and to reduce tastes and odors associated with the use of free chlorine in some drinking water supplies. Chloramination also reduces the formation of free chlorine by-products that are considered toxic, such as trihalomethanes. However, compared to free chlorine, ozone and chlorine dioxide, chloramines are relatively weak oxidants and germicides. Based on the product of disinfectant concentration, C, and contact time, T, (C \times T) it takes about 10 to 100 times more chloramine than free chlorine to inactivate an equivalent amount of most waterborne microbes. Chloramination is also more difficult to apply to water than free chlorine because it requires the combined addition of controlled amounts of both free chlorine and ammonia. Treatment of water with chloramines is not commonly practiced at point-of-use and is not recommended for household water treatment. This is because it requires the availability of both free chlorine and ammonia, it is complicated to properly apply both free chlorine and ammonia to water at the required doses, the resultant disinfectant is weak and slow acting, and the cost of using both chlorine and ammonia is higher than the cost of using chlorine alone.

5.4.5 Ozone

Ozone has been used as a drinking water disinfectant since the early 20th century. It has gained popularity for community water supplies in developed countries because it is a strong oxidant capable of rapidly and extensively inactivating a variety of waterborne pathogens, including chlorine-resistant *Cryptosporidium parvum* oocysts. Ozone is a highly reactive gas that must be generated on site using electricity. It

requires specialized equipment to deliver to water at required doses, and care must be taken to prevent safety hazards from the release of ozone gas by the treated water. Because ozone is rapidly consumed by dissolved and particulate constituents in water, achieving appropriate ozone doses in actual practice requires careful attention to water quality as well as the ability to monitor both ozone dose and ozone residual in the treated water. Therefore, this method of drinking water disinfection is suitable primarily for community or other centralized water systems where the specialized equipment and delivery systems required for its use can be properly applied by trained personnel. Although small, point-of-use ozone treatment systems are available for consumer use they are relatively expensive and difficult to maintain, require electricity and therefore are not recommended for household water treatment.

5.4.6 Chlorine Dioxide

Chlorine dioxide is used primarily as a bleaching agent and has gained some use for disinfection of both community and point-of-use drinking water supplies in developed countries. Chlorine dioxide is a relatively strong germicide capable of inactivating most waterborne pathogens, including *Cryptosporidium parvum* oocysts, at practical doses and contact times. For community water treatment, chlorine dioxide is generated on-site from the reaction of sodium chlorite with chlorine gas or from the reaction of sodium chlorite with acid. Producing chlorine dioxide from free chlorine and sodium chlorite is technically demanding and requires specialized equipment. For point-of-use treatment of water, chlorine dioxide is produced on site from the reaction of sodium chlorite with acid. Such use is primarily for disinfecting temporary or informal water sources used by outdoors enthusiasts and others requiring short-term applications in developed countries. The toxicity of chlorine dioxide and its by-products, such as chlorite, limits the use of this disinfectant, because the amount of toxic by-products is difficult to control or measure. In addition, the generation of chlorine dioxide from sodium chlorite and acid is relatively expensive, compared to free chlorine. For these reasons, chlorine dioxide is not widely used and is not recommended for long-term disinfection of household drinking water.

5.4.7 Combined point-of-use treatment systems

The combined application of chemical coagulation-flocculation, filtration and chlorine disinfection is widely practiced for community water treatment in developed countries, especially for surface sources of drinking water. In combination, these processes have been shown to dramatically reduce microbial contaminants in drinking water, produce product water that meets international guidelines and national standards for microbial quality and embody the principles of a multiple barrier approach to drinking water quality (LeChevallier and Au, 2000). Because of the relative complexity of these processes, they are more difficult to implement at point-of-use for household drinking water supplies in developed countries. However, purification of water at point-of-use using tablets or powders that combine a coagulant-flocculent and a chemical disinfectant have been described (Kfir et al., 1989; Rodda et al., 1993; Powers, 1993; Procter & Gamble Company, 2001). In South Africa commercial tablets containing chlorine in the form of Halazone p-triazine-trione or dichloro-S-triazine-trione and either aluminum sulfate or proprietary flocculating agents have been developed, evaluated and promoted for community and household water treatment, as well as emergency water treatment. For household use on non-piped, household water supplies it is recommended that the tablets be added to

water in a 20-liter bucket. The mixture is stirred to dissolve the tablet and flocculate, then allowed to stand unmixed to settle the floc and then supernatant water is poured through a cloth filter into another bucket. When these tablets were tested for efficacy in reducing bacteria, viruses and parasites, they were found to achieve extensive reductions and meet US EPA requirements for a microbiological water purifier. According to the manufacturer, the cost of treatment with these tablets is low. Epidemiological studies of the effectiveness of these systems to reduce waterborne diarrheal and other diseases have not been reported.

The Procter and Gamble Company in cooperation with the USA CDC and other collaborators reports the development and evaluation of a combined flocculent-disinfectant powder supplied in a small packet that is added to a 10-liter volume of household water by consumers. The powder contains both coagulants and a timed-release form of chlorine. After stirring briefly, contaminants settle to the bottom of the container and the supernatant water is poured through a cloth filter into another container for safe storage and use. Initial studies document dramatic reductions of microbial as well as some chemical contaminants in water, and field epidemiological studies to determine reductions in household diarrheal disease are under way in Guatemala villages. The cost of the treatment is estimated at US\$0.01 per liter.

Overall, combined coagulation-flocculation and chlorine disinfection systems have shown considerable promise as microbiological purifiers of household water. Currently, they have not come into widespread use and their worldwide availability is limited at the present time. However, further studies that document efficacy in reducing diarrheal disease and improving microbial quality are apparently forthcoming for some of these systems. Such data documenting performance and the commercial availability of the materials through widespread marketing and distribution create the potential for this technology to be not only scientifically supportable but also widely available in many parts of the world. The relatively high costs of these combined systems may limit their use by some of the world's poorest people, but market studies also are under way to determine consumers' willingness to pay. Therefore, these combined systems may prove to be appropriate technologies for household water treatment in many settings for the large segment of the world's population now collecting and storing water for household use.

5.4.8 Lime juice disinfection of *V. cholerae*

Drinking water disinfection by lowering water pH with lime juice is effective in inactivating *V. cholerae* and in reducing cholera risks (Dalsgaard et al., 1997; Mata et al., 1994; Rodrigues et al., 1997; 2000). Adding lime juice to water (1-5% final concentration) to lower pH levels below 4.5 reduced *V. cholerae* by >99.999% in 120 minutes (Dalsgaard et al., 1997). Lime juice also killed >99.9% of *V. cholerae* on cabbage and lettuce and was recommended for prevention of cholera by addition to non-acidic foods, beverages and water (Mata, 1994). Epidemiological studies during cholera outbreaks in Guinea-Bissau showed that lime juice in rice foods was strongly protective against cholera and laboratory studies showed that the presence of lime juice inhibited *V. cholera* growth in rice foods. These studies indicate that adding lime juice to water, beverages and other foods (gruels, porridges, etc.) has the ability to inactivate *V. cholera* and reduce disease risks. Therefore, the use of lime juice in water and foods is a potentially promising household treatment to control cholera

transmission. Further studies to better characterize the efficacy of this treatment and its ability to reduce cholera transmission are recommended.

6. Social and Economic Aspects

6.1 Educational, Behavioral and Related Socio-Cultural Considerations for Household Water Treatment Systems

A number of studies and considerable field experiences have shown that the introduction of water treatment technology without consideration of the socio-cultural aspects of the community and without behavioral, motivational, educational and participatory activities within the community is unlikely to be successful or sustainable. Therefore, initiatives in water, hygiene and sanitation must include community participation, education and behavior modification. A number of systems have been developed and successfully implemented for this purpose. One of the most widely used and successful of these is termed PHAST, which stands for Participatory Hygiene and Sanitation Transformation (WHO, 1996). It is an adaptation of the SARAR (Self-esteem, Associative strengths, Resourcefulness, Action-planning and Responsibility) method of participatory learning. PHAST promotes health awareness and understanding among all members of a community or society in order to change hygiene and sanitation behaviors. It encourages participation, recognizes and encourages self-awareness and innate abilities, encourages group participation at the grassroots level, promotes concept-based learning as a group process and attempts to link conceptual learning to group decision-making about solutions and plans of action for change and improvement of the current situation. It encourages internally derived decisions and both material and financial investment of the community to affect change.

Current approaches to participatory education and community involvement in water and sanitation interventions apply behavioral theory and other related sciences to successfully implement control measures. The use of water treatment technologies and other water quality control measures that are consistent with prevailing beliefs and cultural practices and local resources are promoted by behavioral theory. Community involvement at all levels is important in achieving community support and sustainability for the technology. Efforts to introduce improved household water treatment and storage systems have employed health education, community mobilization, social marketing, motivational interviewing, focus groups, and other educational, promotional, communication and mobilization techniques to change behaviors, facilitate learning and elicit participation.

Another example of this approach is a program to facilitate support agencies in developing community willingness and capacity to take responsibility for their own water supplies called the MANAGE Dissemination system developed by the International Water and Sanitation Centre (IRC, 1999). The goal of the system is to facilitate achievement of community management of and decision-making for rural water supply supplies. The MANAGE Dissemination program disseminates and shares findings of entities engaged in developing and implementing community participatory action through an information network intended to enhance multi-institutional learning approaches and develop training methods and tools that facilitate and support community management of water supplies. The system employs exchange visits and other communications activities among participants who