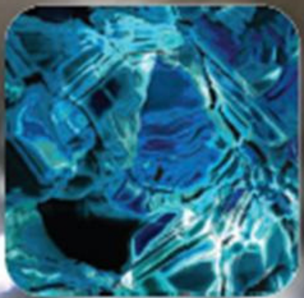
Background Paper for the International Workshop on

Nanotechnology, Water, and Development

Overview and Comparison of Conventional treatment technologies & Nano-Based treatment technologies



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This paper was written by Meridian Institute's Global Dialogue on Nanotechnology and the Poor: Opportunities and Risks (GDNP). The goals of the GDNP are to: (1) raise awareness about the implications of nanotechnology for the poor; (2) close the gaps within and between sectors of society to catalyze actions that address specific opportunities and risks related to nanotechnology, especially those of most significance to developing countries; and (3) identify ways that science and technology can play an appropriate role in the development process. The GDNP is supported by the International Development Research Centre (Canada), UK Department for International Development, and The Rockefeller Foundation (U.S.).

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introduction

This paper is intended as a supplement to the "Nanotechnology, Water, and Development" paper commissioned by Meridian Institute's Global Dialogue on Nanotechnology and the Poor (GDNP) as background for the International Workshop on Nanotechnology, Water, and Development in Chennai, India (http://www.merid.org/nano/waterpaper/). Specifically, this paper responds to numerous requests for a comprehensive document that facilitates comparisons of conventional and nanotechnology-based water treatment devices.

Lack of access to clean water and sanitation in developing countries remains a high development priority. Despite numerous intervention strategies and large public and private investments, many challenges continue to impede water and sanitation projects, in particular those establishing centralized water systems. Funding, governance, trained engineers, skilled labor, and access to appropriate technologies are commonly recognized obstacles to establishing regional and national-scale water systems. The difficulty and lack of success in overcoming obstacles to regional and national water supplies has led, in part, to increased interest in point-of-use (POU) water treatment methods at the household and community level.

Advocates of community and household level POU water treatment methods suggest that these approaches avoid many of the barriers associated with large-scale water supply projects because they are relatively inexpensive, can be purchased by the unit, and/or constructed using readily available materials. For these reasons, POU technologies avoid the need for large capital investments, management systems, and governance structures. They also allow community or individual ownership and involvement in decisions, maintenance, and other aspects of the water treatment.

While there appear to be advantages to POU approaches, experts also point out that many POU technologies rely heavily on international aid agencies and non-governmental organizations for subsidization and distribution. Many products have components that need to be frequently replaced in order for water to be effectively treated, and some components can not be made locally in developing countries, leaving users vulnerable to disruptions in distribution.

Nanotechnology is increasingly being identified as an area of science and technology that could play a role in addressing some of the short-comings of conventional POU devices. Proponents suggest that nanotechnology-based materials could lead to cheaper, more durable, and more efficient water treatment technologies that meet the needs of developing countries. Several water treatment methods and devices that incorporate nanoscale materials are already commercially available, and others are being developed. These nanotechnology-based products include water filters, filtration membranes, catalysts, and nanoparticles for groundwater remediation.

While there is growing interest in these nanotechnology-based POU products, various stakeholders are also raising questions about possible implications of products containing nanoscale materials, including potential environmental and human health risks, as well as socio-economic and ownership issues.

This paper draws on a broad range of disparate information sources and synthesizes information about relevant attributes of conventional and nanotechnology-based water treatment devices including: contaminant removal; amount of water treated; cost; ease of use; and other considerations. The first section describes a range of well-known and field-tested conventional POU approaches to removing contaminants from water. The information provided draws on technical papers and peer-reviewed literature, as well as manufacturers' specifications and patent filings. The second section provides examples of available nanotechnologies that could be used to enhance existing or develop new POU water treatment technologies. Since these products are still very new or not yet on the market, much of the information is obtained from materials provided by the manufacturers, as well as limited scientific publications. In many cases, independent verification of the performance of these products is not yet available.

The paper does not include information about potential environmental or human health risks because little, if any, data about these issues is available in the context of specific water treatment devices.

The data provided is taken from numerous sources that report on studies that were conducted under different conditions using a variety of methodologies, techniques, and approaches. Therefore, the data reported in this paper should be interpreted with consideration that direct comparison of data is not always possible; however, the data should provide an overview of the relative effectiveness of the technologies described.

The paper demonstrates that many conventional technologies exist that effectively remove bacteria, viruses, coliforms, turbidity, and other contaminants from water, and that are affordable and can be produced locally. However, a review of the literature suggests that several technical challenges remain with regards to the cost and effectiveness of removal of certain contaminants in a manner that meets the needs of people in developing countries.

[1] conventional pou water treatment technologies

Many technologies for removing contaminants from drinking water exist, and most have been extensively used and/or tested in developing countries. This section provides an overview of information on a broad range of available technologies. The information was gathered from numerous sources, and because of variations in testing conditions and methods, the data is not always directly comparable.

We briefly describe each type of technology and provide a summary of data regarding: 1) contaminants removed using the technology; 2) the amount of water the technology can treat 3) the acquisition and operating cost of the technology; 4) the technology's ease of use; and 5) any other relevant considerations.

[1.1] Filtration

1.1.1 Ceramic Filters

Ceramic filters have micro-scale pores that are effective for removing bacteria from water. The filters are made from clay that is often mixed with materials such as sawdust or wheat flour to improve porosity. Colloidal silver, an antibacterial agent, can also be added to the filters. There are two main types of ceramic filters, disk and candle, with multiple variations of each. A disk filter consists of a removable ceramic filter sandwiched between two containers. Candle filters consist of one or more candle-shaped ceramic filters and two chambers.[1]

Contaminant Removal
Disk and candle filters are generally effective for removing turbidity, iron, coliforms, fecal contaminants, and *E. Coli* from water. In studies, disk filters with colloidal silver have exhibited a 93 to 100 percent bacterial removal rate, and those without silver have shown an 80 percent removal rate. Candle filters with colloidal silver generally exhibit 100 percent bacterial removal, and those without silver average at 85 percent removal.[2] Disk filters range from 83 to 99 percent turbidity removal.[3] Ceramic filters are generally not effective for removing organic contaminants.[4]

Amount of Water Treated
Disk filters typically have a flow rate of 1 to 11 liters per hour and candle filters have a flow rate of 0.3 to 0.8 liters/hour.[5] Under ideal filter conditions and 12 hours of continuous refilling, a filter with a flow rate of 1.7 liters per hour would provide less than 4 liters per day per person for a family of five.[6]

Cost
Disk filter units cost about US$3.50, and replacement filters range from US$0.49 to $1.02. Disk filters need to be replaced every 5 years. Candle filter units cost about US$2.29, with replacement filters averaging about US$0.46. Candle filters need to be replaced every 6 to 12 months. Additional labor and maintenance costs are minimal.[7]

Ease of Use
Ceramic filters are easily assembled, and no component construction is required of the user other than placing the filter into the container.[8] Scrubbing the filter with a toothbrush is required monthly as maintenance. Annual colloidal silver recoating is also recommended. Filters typically come with illustrated instructions.[9]

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[1] Adam Kaufman et al., "Water Treatment Modeling for Developing Communities," University of Waterloo, Ontario, December 17, 2003, pp. 50-52, <http://uwaterloo.ewb.ca/Research/WaterTreatment/TreatmentModeling/InitialProjectFinalReport.pdf>.
[2] Kaufman, pp. 52-53. Studies referenced tested Hari white clay and Reid Harvey red and black clay disk filters in Nepal and Ceradyn, Gravidyn, Hong Phuc, and silver impregnated and non-silver impregnated Hari candle filters in Nepal.
[3] Rebecca Eun Young Hwang, "Six-Month Field Monitoring of Point-Of-Use Ceramic Water Filter Using H_2S Paper Strip Most Probable Number Method in San Francisco Libre, Nicaragua," master's thesis, Massachusetts Institute of Technology, Boston, 2002, p. 23, <http://web.mit.edu/watsan/Docs/Student%20Theses/Nicaragua/Hwang2003.pdf>.
[4] Randy Johnson, "Drinking Water Contaminant Removal Table," March 11, 2002, <http://www.cyber-nook.com/water/WaterTreatment_b.htm>.
[5] Kaufman, p. 53.
[6] Hwang, p. 59. Average filtration rate of 1.7L/hr was determined for PFP disk filters.
[7] Kaufman,. p. 55. Cost estimates are for TERAFIL and Madhyapur Clay Crafts disk filters and Nepal, Hong Phuc, and Katadyn candle filters tested in India and Napal.
[8] Kaufman, p. 54.

The fragility of ceramic filters can make their transport difficult.[10] Field studies have also indicated that heavy subsidization or free distribution of filters may result in maintenance negligence.[11] The production of ceramic filters is a lengthy process that requires skill and quality control. Quality can be affected by variations in clay composition across geographic regions. Variability in weather conditions also makes long-term production planning difficult, and lack of storage can complicate stockpiling of filters.[12]

Additional Considerations
Ceramic filters are not able to achieve maximum effectiveness without silver colloid, which can not be produced locally in all regions.[13]

1.1.2 Biosand Filters

Biosand filters consist of a concrete-coated metal mould filled partially with one layer each of large gravel, small gravel, and clean medium-grade sand. A diffuser plate is placed on top of the sand and water is poured into the remaining space. Prior to use, the filter is filled with water everyday for two to three weeks, until a biological layer of bacterivorous microorganisms resembling dirt develops on the surface of the sand. These microorganisms consume disease-causing viruses, bacteria, and parasites, while the sand traps organic matter and particles.[14]

Contaminant Removal
Biosand filters have been shown to remove more than 90 percent of fecal coliform, 100 percent of protozoa and helminthes, 95 to 99 percent of zinc, copper, cadmium, and lead, and all suspended sediments.[15] Biosand filters have also been shown to remove 76 to 91 percent of arsenic, reducing it to acceptable concentrations.[16] These filters do not sufficiently remove dissolved compounds such as salt and fluoride or organic chemicals such as pesticides and fertilizers.[17] The biological layer's effectiveness is influenced by temperature. Ammonia oxidation stops below 6° Celsius and alternative treatment methods are required below 2° Celsius.[18] Additionally, because biosand filters are not able to handle high turbidity, they may become clogged and ineffective during monsoon or rainy seasons.[19]

Amount of Water Treated
Household biosand filters typically provide 30 liters of water per hour, which is sufficient for a family of five. Flow rate may decrease over time as the filter becomes clogged, but can be restored with cleaning.[20]

Cost
Concrete biosand filters cost between US$12 and $30, with minimal operating costs.[21] Labor and cleaning costs are minimal, though there may be educational and training costs associated with teaching users how to properly maintain their filters.[22] Costs may vary across regions depending on the availability of materials and labor.[23]

Ease of Use
Biosand filters require daily fillings during the 2 to 3 weeks when the biological layer is growing. Biosand filters also require regular cleaning, which involves agitating the water above the biological layer. The filter will require 2 to 3 weeks of nonuse after agitation to allow for the regrowth of the biological layer. On occasion, the sand in the filter needs to be cleaned as

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[9] Hwang, p. 17.
[10] Kaufman, p. 56.
[11] Hwang, p. 100.
[12] Hwang, p. 98.
[13] Kaufman, p. 56.
[14] "Biosand Filters," *Footsteps,* No. 67, June 2006, pp. 8-9, <http://tilz.tearfund.org/webdocs/Tilz/Footsteps/English/FS67_E.pdf>.
[15] "Biosand Filter," <http://www.fortlewis.edu/academics/school_arts_sciences/physics_engineering/ewb_webpage/Current%20Web%20Page%20Supporting%20Docs/BSF/Basic%20info%20on%20BSF.htm>.
[16] Prem Krishna Shrestha, "Arsenic, Iron, and Coliform Removal Efficiency of Household Level Biosand Filters," master's thesis, Tribhuvan University, Lalitpu, Napal, 2004, p. v, <http://web.mit.edu/watsan/Docs/Other%20Documents/KAF/Shrestha%20-%20Arsenic%20Iron%20Coliform%20removal%20of%20ABF%202004.pdf>. Arsenic removal rates are based on laboratory tests and field tests in Nepal on two different household biosand filter types.
[17] "BioSand Filter – Information Sheet," <http://www.friendswhocare.ca/BSF-FWC-%20Specifications.pdf>.
[18] "The Bio-Sand Filter," 2004, <http://www.biosandfilter.org/biosandfilter/index.php/item/229>.
[19] Yung, p. 12.
[20] Kathleen Yung, "Biosand Filtration: Application in the Developing World," University of Waterloo, Ontario, March 2003, p. 10, <http://uwaterloo.ewb.ca/BSFdocuments/BSF%20-%20application%20in%20the%20developing%20world.pdf>.
[21] "Biosand Filter - UN Habitat: Best Practice Brief," July 4, 2005, <http://www.jalmandir.com/archives/000174biosand_filter_un_habitat_best_practice_brief.php>.
[22] Yung, p. 27.
[23] Yung, p. 24.

well. There are several different methods to clean the sand, though all of them require significant labor, significant training, or high cost.[24] User error has also been found to affect the filters' efficiency, especially because of the required 2 to 3 week non-use period for growing the biological layer. Biosand filters can be fabricated locally in almost all regions because they use common materials.[25]

Additional Considerations
A field study in Nepal found that the cost of acquiring a biosand filtration system equaled 15 percent of the average Nepalese family's annual income and that most families indicated a willingness to spend 5 percent of their income on a filtration system.[26]

I.1.3 Charcoal and Activated Carbon Filters

Charcoal and activated carbon (AC) are used for water filtration because of their adsorptive properties. These filters capture solid particles in water. Additionally, the filters' surfaces chemically interact with organic molecules in order to remove them. POU AC systems may use granular activated carbon (GAC) filters made with loose carbon granules or solid block activated carbon (SBAC) filters made of pressed carbon.

Contaminant Removal
Charcoal and AC filters are mostly used to treat organic contaminations such as pesticides, industrial solvents, polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs). They are used to improve the taste and odor of water. These filters generally do not remove dissolved solids, heavy metals, lead, or coliforms, though they are able to remove arsenic, chromium, and mercury found in organic complexes.[27] Their removal efficiency depends on the quality and amount of charcoal or carbon used in the filter and the length of time that the filter has been in use. Higher water turbidity and flow rate also decrease removal efficiency. If these filters become saturated, the trapped contaminants can be released back into the filtered water. Also, the particles that accumulate within the filters may serve as food for bacteria, resulting in high concentrations of bacteria within the filter that can eventually be released into the treated water. SBAC filters do not have the problem of bacteria growth and may be able to filter out coliforms and pathogens.[28]

Amount of Water Treated
The amount of water that a charcoal or AC filtration system can provide is heavily dependent on the quality of the carbon media used in the filter and the quality of the water being filtered. Slow flow rate is very important for the effectiveness of these devices, therefore, there is a large tradeoff between the size of the unit and the amount of water it can treat.

Cost
Charcoal filters have an annual estimated cost of US$10 to 100 for a family that uses 25 liters of water per day. Countries with local access to charcoal, or materials such as coconut husks from which charcoal media can be derived will face significantly lower costs that those that have to import the charcoal filters. AC filtration systems have estimated average annual cost of over US$100 for a family that uses 25 liters a day.[29] These systems use GAC filters that need to be replaced every 9 to 12 months.[30] Pour-through GAC filtration units cost about US$10 and use replacement filters that cost about US$2 each and need to be replaced after 40 gallons of water. Labor and maintenance costs are limited to purchasing and replacing the filters. SBAC units begin at about US$330, but generally cost about US$2500. Replacement filters are needed about once a year. SBAC replacement filters cost about US$0.07 per gallon of water treated.[31]

Ease of Use
Charcoal and AC filtration systems are easy to use and maintain according to the manufactures' guidelines. These systems require regular cleaning and filter changes, however, which require some education and skill. If a regular maintenance schedule is not observed, users may be unaware that the system needs cleaning until signs of contamination are evident. Education and training is needed in order to locally produce charcoal filters.

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[24] Yung, pp. 13-14.
[25] "The Bio-Sand Filter," 2004, <http://www.biosandfilter.org/biosandfilter/index.php/item/229>.
[26] Yung, p. 23.
[27] "National Primary Drinking Water Standards - Primary (Health Related) Inorganic Contaminants," Water Quality Association, Lisle, IL, <http://www.wqa.org/consumer/palltables.cfm?SubTitleID=1 &MainTitleID=1>.
[28] "Methods of Water Filtration & Purification," Gaiam, <http://www.gaiam.com/retail/gai_content/learn/gai_learnArticle.asp?article_id=1990>.
[29] Sobsey, p. 38.
[30] Jeffrey Kempic and Rajiv Khera (US Environmental Protection Agency), "Point-Of-Use/Point-Of-Entry Devices Cost Considerations," presentation at the Public Water System Compliance Using Point-of-Use and Point-of-Entry Treatment Technologies Conference, Orlando, FL, February 13, 2003, <http://nsf.org/regulatory/conferences/docs/Kempic_Khera.pdf>.
[31] Randy Johnson, "Drinking Water Treatment Methods," 2005, <http://www.cyber-nook.com/water/Solutions.html>.

Additional Considerations
AC filtration devices are often subsidized or donated by international aid organizations or NGOs in order to make them more affordable for developing countries.[32]

I.I.4 Granular Media and Rapid Rate Filters

Sand, anthracite, sandstone, and charcoal are used as granular media for water filtration in POU devices such as bucket, drum or barrel, roughing, and cistern filters. These granular media are usually negatively charged and may be mixed with positively charged metal oxides and hydroxides of iron, aluminum, calcium and magnesium for more effective adsorption of negatively charged viruses and bacteria. These filters may also contain antibacterial elements such as silver.

Contaminant Removal
Granular media and rapid rate filters typically remove up to 90 percent of turbidity and enteric bacteria and more than 99 percent of larger parasites. Roughing filters can remove 50 to 85 percent of bacteria in highly turbid water. Combining the filter media with a positively charged ingredient can result in up to 99 percent viral and bacterial removal. Filters containing granulated vegetable matter such as burnt rice hull ash have been shown to reduce turbidity and general bacteria by 90 percent, with *E. Coli* reductions reported at 90 to 99 percent.

Amount of Water Treated
Granular media and rapid rate filters are available in a variety of scales for household and community-level use. The most widely used commercial bucket filtration system provides enough water for 10 people per day. Drum or barrel filters typically have a 200 liter capacity, though a version designed by UNICEF provides 40 liters of treated water a day. Roughing filters are operated at relatively low flow rates, but typically large enough to provide water for an entire community. [33]

Cost
Bucket filters can be locally built at low cost using sand or other local granular media. Commercial bucket filters are also available. The most widely used version consists of two 19 liter buckets and filters and costs US$50, with replacement filters that cost US$20. These bucket filter systems are often subsidized by NGOs to make them affordable.[34] Drum or barrel filters cost US$0.001 to $0.10 per liter of water treated.[35]

Ease of Use
Bucket filters consist of two or three buckets, one of which is perforated at the bottom and filled with granulated media. Water is passed through this bucket into an empty bucket. Initially, enough water should be passed through the filtering bucket to clean the media. The media also needs to be cleaned or replaced every few weeks to remove accumulated contaminants and microbes. Drum or barrel filters come in a variety of designs, most of which have a pour-through design. These filters require regular cleaning through backwashing, a process of forcing water through the filter, which may be technically difficult. Roughing filters also require regular backwashing to work effectively. Roughing filters are most often used on a community level because of their need for operational and maintenance skill and labor.[36] If a regular maintenance schedule is not followed, users may be unaware that any of these filters needs cleaning until signs of contamination are evident.

Additional Considerations
Granular media and rapid rate filters are not recommended as sole water treatment methods because of their low microbe reduction.[37]

I.I.5 Fiber and Fabric Filters

Compressed or cast fibers (e.g. cellulose paper), spun threads (e.g. cotton), and woven fibers (e.g. linen, cotton, and other cloths) are widely used for POU water treatment because of their low cost and simplicity. One method used by women in the Indian subcontinent, known as sari filtration, involves using garment cloth folded 4 to 8 times to filter solid particles and microorganisms from water.

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[32] Sobsey, p. 38.
[33] Sobsey, pp. 25-28.
[34] Sobsey, p. 26.
[35] Sobsey, p. 24.
[36] Sobsey, pp. 25-27.
[37] Sobsey, pp. 26-28.

Contaminant Removal
The effectiveness of paper and cloth filters is largely dependent on the relative size, shape, and surface chemistry of the contaminant particles and the filter material. These filters are generally ineffective for viruses and bacteria because their pores are larger than the diameter of the microbes.[38] Sari filters are usually effective for removing solid particles and microorganisms that are larger than 20 micrometers, including free-swimming pathogen larvae, guinea worm larvae within crustacean hosts, bacteria with large copepods, and zooplankton, including those harboring *V. cholerae*. A study of quadruple-folded saris found that 99 percent of *V. Cholerae* was removed from water.[39] These filters do not remove chemical contaminants or dissolved compounds from water. Additionally, studies have found that a sari's fibers loosen significantly the more they are used, increasing their pore size and making them less effective. [40]

Cost
Fabric and fiber filtration costs are minimal and associated with acquiring or making appropriate materials.

Ease of Use
Fabric and fiber filtration involves placing the filter over the opening of a water vessel and pouring the contaminated water through. A cone-shaped filter may also be placed inside a funnel through which the water is poured. Paper and fibrous filters may come in the form of cartridges that are either partially submerged in water or used to pour-through water.

Additional Considerations
Field studies indicate that saris with loosened fibers from overuse are more likely to be used for filtering water because they are less fit for wearing.[41]

[1.2] Heat and UV Radiation

1.2.1 UV Radiation

UV radiation can improve the microbiological quality of drinking water by disabling pathogenic microorganisms that cause water-borne diseases. A number of UV radiation methods exist, including solar disinfection (SODIS) and UV lamps. The SODIS process involves filling transparent plastic bottles with water and exposing them to full sunlight for six or more hours so that a combination of UV-A radiation and increased water temperature disinfects the water. This process may be combined with solar reflectors or solar cookers to further increase water temperature. Several types of UV lamps are available, but those used most often in developing countries are low pressure mercury arc lamps that are either submerged in the water or mounted above a shallow tank.

Contaminant Removal
UV radiation is generally used for the treatment of vegetative and coliform bacteria and enteric pathogens. SODIS, without the use of reflectors or cookers, has been found to kill 99.4 percent of fecal coliform in a liter of water with one day of full light exposure and 91 percent under cloudy conditions.[42] These removal rates heavily depend on sunlight intensity and duration, cloudiness, ambient temperature, and bottle quality, including how scratched and thick the plastic is. UV lamps have been shown to kill 99.9 percent of vegetative bacteria, enteric viruses, and bacterial spores. Removal rates for both SODIS and UV lamps are lowered by the presence of organic matter, iron, sulfites, nitrites, and turbidity because these particles absorb UV radiation and shield microbes from being hit with UV rays.[43] UV radiation does not treat chemical contamination or turbidity.

Amount of Water Treated
SODIS requires 10 or fewer liters of water per container in order to be effective. The size and number of bottles used, as well as the length of exposure required given the sun's availability, will determine the amount of water treated by SODIS.[44] Low pressure mercy arc UV lamp can treat 1 or more liters per minute.[45]

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[38] Mark D. Sobsey, "Managing water in the home: accelerated health gains from improved water supply," World Health Organization, Geneva, 2002, p. 30, <http://www.who.int/water_sanitation_health/dwq/WSH02.07.pdf>.
[39] Rita R. Colwell, "Reduction of cholera in Bangladeshi villages by simple filtration," *PNAS Early Edition*, December 5, 2002, <http://www.pnas.org/cgi/reprint/0237386100v1.pdf>.
[40] Kaufman, p. 39.
[41] Kaufman, p. 39.
[42] "SODIS technology to purify water stressed," November 17, 2004, <http://www.jalmandir.com/archives/sodis-solar-water/sodis_technolog.php>.
[43] Sobsey, pp. 17-20.
[44] Sobsey, p. 15.
[45] Sobsey, p. 21.

Cost
The costs associated with SODIS are minimal because the only materials needed are plastic bottles. Solar reflectors and cookers can also be made cheaply using cardboard and aluminum foil.[46] UV lamp costs include the actual unit, electricity, and replacement bulbs, which are typically needed once a year. A small batch UV lamp system used at the community level and all related expenses typically cost less than US$1 per household per year. When used at the household-level, UV lamps and related expenses average US$10 to $100 a year.[47]

Ease of Use
SODIS is a very simple process to set-up, though SODIS users need to monitor the temperature of the water to ensure it is properly treated. UV lamp need to be cleaned regularly and handled with care because of their mercury content.

Additional Considerations
Access to thermometers is necessary for users to determine whether water has reached an effective temperature for contaminant removal. Studies indicate that some users stop using SODIS because chemicals may leach from the bottles into the water, causing undesirable taste or smell.[48]

[1.3] Chemical Treatment

1.3.1 Coagulation-Flocculation

Coagulants and flocculants are chemicals added to water to remove turbidity and microbes. Coagulants neutralize the charges that keep colloidal particles apart, forcing them to collide into larger particles called flocs. Flocculants agglomerate flocs into larger clumps for easier removal through filtration. These chemicals can be made from alum, iron salts, lime, caustic soda, soluble synthetic organic polymers, and natural polymers. Coagulation-flocculation is often combined with filtration or chemical disinfection.

Contaminant Removal
Under optimal dosage conditions, alum and iron-based coagulation-flocculation has been shown to remove 90 to 99 percent of all waterborne pathogens. Suboptimal conditions yielded less than 90 percent reductions. Potash alum, which is naturally-derived,, has been shown to reduce fecal coliform by 90 to 98 percent.[49] Seed and nut extract from the nirmali plant has shown 50 to 95 percent reductions in bacteria and turbidity.[50] When combined with filtration, coagulation-flocculation may be able to remove some inorganic contaminants, including arsenic, asbestos fibers, cadmium, chromium, lead, and selenium.[51]

Amount of Water Treated
Different chemicals require different concentrations per liter of water. The quality of the chemicals and the water's pH and contaminant composition will also affect the concentrations needed per liter.

Cost
Estimated annual costs for a household using 25 liters per day vary for different chemicals. Soluble synthetic organic polymers and lime cost more than US$100 per year, alum and iron salts cost US$10 to $100 per year, and natural polymers cost less than US$10 per year.[52]

Ease of Use
Effective use of naturally-derived coagulants requires that the seeds be freshly crushed into a powder before every use. The water also needs to be stirred for an extended period of time after the chemicals have been added in order to maximize flocculation. Chemical coagulant-flocculants require careful control of dosage based on the water's pH and quality. Producing coagulant-flocculants from natural polymers found in seeds, nuts, beans, and other plants containing carbohydrates requires skilled labor [53]

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[46] Sobsey, p. 15.
[47] Sobsey, p. 21.
[48] Sobsey, pp. 15-17.
[49] Sobsey, p. 36. Potash alum tests were conducted for 50mg/L concentrations in a suburban community in Myanmar.
[50] Sobsey, p. 37.
[51] "National."
[52] Sobsey, p. 35.
[53] Sobsey, p. 35.

Additional Considerations
Plants used to produce coagulant-flocculants may be toxic if incorrectly chosen.[54]

I.3.2 Chemical Disinfection

Chemical disinfectants inactivate pathogens and microbes in water. They include strong oxidants, such as chlorine, ozone, chlorine dioxide, as well as chloramines, iodine, and acids and bases that kill microbes by changing water's pH levels. Commonly used chemical disinfectants include liquid and powder forms of chlorine such as sodium hypochlorite, calcium hypochlorite, and bleaching powder. Sodium hypochlorite can be made onsite by passing electricity through salt water using an electric or solar powered generator. Chemical disinfection can occur at the household or community level and is often combined with coagulation-flocculation or filtration.

Contaminant Removal
Chlorine disinfectants are all generally able to inactivate 99.99 percent of viruses, coliforms, and bacteria within 30 minutes of being added to water. They also provide residual protection for some period of time against regrowth of bacteria and pathogens, unless there is a large influx of these contaminants. These disinfectants may be less effective on microbes that are clumped together or embedded in cells, fecal matter, or other matrices. Particulate, colloidal, and dissolved contaminants can also block the interaction of disinfectants and microbes.[55] They are also less effective as water turbidity, pH, and concentrations of ammonia, iron, and hydrogen sulfide increase and as water temperature decrease.[56] Chemical disinfectants are not effective for treating turbidity, chemical contamination, heavy metals, and some protozoa.

Amount of Water Treated
Concentrations of disinfectants needed to treat a given amount of water depend greatly on the quality of the disinfectant and the water. Several field studies indicate that 250 milliliters of liquid disinfectant is usually sufficient to treat one household's water consumption for a month. Bleaching powders require calculations to determine proper dosage. Sodium hypochlorite generators are available in a variety of scales, but a mid- to large-scale unit can provide enough disinfectant for 8,000 families.[57]

Cost
Bottled liquid sodium and bleaching powder are estimated to cost less than US$10 per year for a family of 5, and they are often subsidized by international aid agencies to further lower the price. Sodium hypochlorite generators range from US$700 to $2,500, depending on scale. Recurring costs for generating sodium hypochlorite include salt, labor, electricity unless solar power is used, and bottles, which can be reused.[58] Considering all these costs, a month's supply of hypochlorite from a generator is estimated to cost US$0.40 to $0.80 per family.[59]

Ease of Use
Liquid and powder disinfectants are added directly to contaminated water and stirred for several minutes. It is recommended that users regularly test their water's residual chlorine levels, though this may be challenging process that requires testing materials and equipment. Calcium chloride is sold in solid form and requires a trained technician to dissolve it prior to household use. It is also corrosive and requires storage in a dry area.[60] Sodium hypochlorite generators require basic training, which is often provided in included instructive materials. Regions without consistent access to electricity can use solar powered generators.[61] Bottled and powdered disinfectants lose half their effectiveness within a few weeks or months and, therefore, can not be stockpiled.[62]

Additional Considerations
Field studies indicate that some users stopped using chemical disinfectants because of undesirable tastes and odors.[63] The Centers for Disease Control and Prevention (CDC) recommend onsite sodium hypochlorite generation for developing countries because it ensures supplies of the disinfectant, even during natural disasters and political upheavals.[64]

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[54] Sobsey, p. 35.
[55] Sobsey, p. 44.
[56] Ashok Gadgil, "Drinking Water in Developing Countries," *Annual Review of Energy and the Environment*, Vol. 23, 1998, p. 272, <http://eetd.lbl.gov/iep/archive/uv/pdf/1998DrinkingWater.pdf>.
[57] Centers for Disease Control, "Safe Water Systems for the Developing World: A Handbook for Implementing Household-Based Water Treatment and Safe Storage Projects," Atlanta, 2000, p. 28, <http://www.cdc.gov/safewater/manual/sws_manual.pdf>.
[58] Centers for Disease Control, "FAQ Sheet - CDC Safe Water," July 24, 2006, <http://www.cdc.gov/safewater/publications_pages/pubs_faq.htm>.
[59] Kaufman, p. 73.
[60] Kaufman, p. 67.
[61] Morganti, p. 2.
[62] Gadgil, p. 273.
[63] Sobsey, p. 46.
[64] Daniele S. Lantagne, et al., "Household Water Treatment and Safe Storage Options in Developing Countries: A Review of Current Implementation Practices," Woodrow Wilson International Center for Scholars, Washington, DC, 2006, p. 3, <http://www.wilsoncenter.org/topics/docs/Household_Water_Treatment.pdf>.

I.3.3 Flocculant-Disinfection

Flocculation and disinfection can be combined to simultaneously remove turbidity, heavy metal and organic matter contamination and inactivate bacteria and pathogens. Proctor & Gamble has developed a product called PuR Purifier of Water® household flocculant-disinfection. PuR® is a single-use sachet containing powdered ferrous sulfate, a flocculant, and calcium hypochlorite, a disinfectant, and is added directly to water. Proctor & Gamble sells PuR® at no profit to developing countries and non-governmental organizations.[65]

Contaminant Removal
Studies indicate that PuR® removes more than 99 percent of viruses, bacteria, and parasites and also provides residual protection from regrowth and recontamination. It has also been shown to remove more than 99 percent of naturally occurring and artificially added arsenic. Turbidity was also removed to acceptable levels.[66]

Amount of Water Treated
Each PuR® sachet treats 10 liters of water.

Cost
Each PuR® sachet costs US$0.10. For typical water use, it is estimated that this translates to US$0.07 per day for a household.[67]

Ease of Use
PuR® sachets are added directly to 10 liters of water and stirred for several minutes. The water is then strained through a clean cotton cloth to remove flocs and left to sit for 20 minutes to allow the disinfectant to inactivate microbes.[68]

Additional Considerations
PuR® sachets were widely accepted in several developing country field trials, and most trial participants indicated that they would continue to purchase the product. Proctor & Gamble is currently collaborating with the CDC and several NGOs to distribute PuR® to developing countries.

[I.4] Desalination and Arsenic Removal

I.4.1 Reverse Osmosis

Reverse osmosis involves forcing contaminated water through a semi-permeable membrane that traps solutes but allows pure water to pass. A typical system consists of a particulate pre-filter, a reverse osmosis membrane, and an activated carbon cartridge, as well as a water storage tank. Portable reverse osmosis water processors can be used for household water purification and are often gravity powered and do not require electricity or a pump. Community-level reverse osmosis systems may be electricity, diesel, battery, or solar powered.

Contaminant Removal
Though generally used for removing salt and arsenic, reverse osmosis can also remove most inorganic contaminants, bacteria, viruses, and parasites. The concentration and chemical composition of the contaminants and the source water temperature, pressure, and pH will affect the removal efficiency of the membranes. These conditions do not affect the ability of reverse osmosis to reduce salt to acceptable levels.[69] Reverse osmosis also generally removes up to 90 percent of arsenic, though higher concentrations of arsenic could make the process less efficient, as can the use of smaller, cheaper units.[70] Reverse osmosis can also remove some organic contaminants such as pesticides, herbicides, insecticides, and VOCs, but not in sufficient quantities.[71] For this reason, reverse osmosis is not recommended for the removal for the removal of organic chemicals.[72]

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[65] Lantagne, p. 12.
[66] Philip F. Souter, et al. "Evaluation of a new water treatment for point-of-use household applications to remove microorganisms and arsenic from drinking water," *Journal of Water and Health*, January 2, 2003, pp. 73-77, <http://www.pghsi.com/safewater/pdf/souterdoc.pdf>. Tests were conducted on laboratory water samples, as well as 320 field samples from Bangladesh, Guatemala, and the Phillipines.
[67] Sobsey, p. 23.
[68] Lantagne, p. 12.
[69] Johnson.
[70] Agency for Toxic Substances & Disease Registry, "Arsenic in Private Drinking-Water Wells," February, 14 2006, <http://www.atsdr.cdc.gov/arsenic/>.
[71] Johnson.
[72] Johnson.

Amount of Water Treated
A portable reverse osmosis system can provide between 4 and 75 liters of water in 24 hours, depending on the size of the unit.[73] Different types of community-scale reverse osmosis systems can be scaled to produce between 1,000 to 10,000 liters of water per day, though the average system produces about 3,000 liters per day.[74]

Cost
Portable 7 liter per day reverse osmosis units appropriate for a single household cost about US$200. Larger units that produce 100 liters an hour and are designed for multiple households cost about US$4,000.[75] Assuming all related costs and a 20 year lifetime, 3,000 liter per day diesel-powered reverse osmosis is estimated to cost about US$12 per 1,000 liters of water and solar powered reverse osmosis is estimated to cost about US$3.50 per 1,000 liters.[76] The development of more efficient technology and sturdier, longer-lasting membranes is making reverse osmosis increasingly cost-effective.[77]

Ease of Use
Portable reverse osmosis systems typically have a pour-through design and require some maintenance including filter and membrane replacement and storage tank cleaning.[78] Because damage to the membrane can be undetectable to the eye, electronic or other forms of testing may be necessary to determine when the membrane needs changing.[79] Community level reverse osmosis systems require trained experts to monitor and inspect the system, as well as to calibrate and adjust different parts, detect and repair leaks, and change and clean filters and membranes.[80] International aid agencies and NGOs may be able to provide training to new users. [81] Remote areas also need a community system for procuring, storing, and distributing replacement filters, membranes, and, if required, batteries.

Community level reverse osmosis may be more difficult to use in remote areas because disruptions to electricity or fuel access, prevents the systems from providing water. Battery-powered systems use lead acid batteries that require proper transport and storage. Studies have found that up to 30 percent of batteries are destroyed from being shaken during transport to remote areas and, once at their destination, many batteries are stored dockside, where air temperature and humidity erode their electrodes. These studies also found that batteries were often not maintained properly and, if batteries could not be procured for 2 to 6 year replacements, the entire system was often left in disrepair.[82] Solar powered systems are limited by the sun variability and the low energy efficiency of solar photovoltaics.[83]

Additional Considerations
Field studies have found that community level reverse osmosis systems are often perceived as expensive and high-tech.[84]

I.4.2 Distillation

Distillation involves evaporating and condensing water in order to separate out contaminants. Distillation can be performed using a variety of scales and methods including solar stills, homemade distillation units, and electricity-powered commercial distillation units. Solar stills are glass or plastic structures that heat the water using solar radiation and then transfer condensed vapor to a storage tank. Homemade distillation units consist of a small pot placed inside a larger pot that is filled with seawater. The pots are covered with plastic and heated over a stove or fire until the water evaporates, condenses, and drips into the smaller pot. Commercial distillation units consist of a glass boiler, a condensing tube, and a collecting reservoir. The units use electricity to heat the water and transfer it through the system with pumps.

Contaminant Removal
Distillation can be used to remove virtually all salt, nitrates, and heavy metals such as arsenic from water. Commercial and homemade distillation units may also be effective for eliminating pathogens and other biological contaminants from water

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[73] Daulton, *Training Guide to Water and Its Problems*, 1997, Chap. 6, "Point-of-Use Technologies and Applications," <http://www.doulton.ca/chapt6.html>.
[74] M. Thomson, et al., "Batteryless Photovoltaic Reverse-Osmosis Desalination System," DTI Sustainable Energy Programmes, 2001, p. 22, <http://test.netgates.co.uk/nre/pdf/SP200305.pdf>.
[75] Third World Academy of Sciences, "Safe Drinking Water: The need, the problem, solutions, and an action plan," 2002, p. 19, <http://www.ictp.trieste.it/~twas/pdf/SafeDrinkingWater.pdf>.
[76] Thomson, p. 24.
[77] TWAS, p.10.
[78] Johnson.
[79] Daulton.
[80] United Nations Environment Programme - International Environmental Technology Centre, Source Book of Alternative Technologies for Freshwater Augmentation in Latin America and the Caribbean, Washington, DC, 1997, Chap. 2.1, "Desalination by reverse osmosis," <http://www.oas.org/dsd/publications/Unit/oea59e/ch20.htm>.
[81] UNEP-IETC, Chap. 2.1.
[82] Thomson, p. 21.
[83] Thomson, p. 1.
[84] UNEP-IETC, Chap. 2.1.

because they involve bringing the water to a boil. Solar stills are less effective for removing biological contaminants because they operate at lower temperatures. Distillation is not appropriate for removing organic contaminants such as pesticides, fertilizers, and VOCs because these chemicals can evaporate and reconstitute with the treated water. [85]

Amount of Water Treated

Solar stills generally provide 2.3 liters of water per square meter of still. For average use, two square meters of still is required per person.[86] The amount of water provided by homemade distillation depends entirely on the size of the pots used. Commercial distillation units are available in a variety of scales, but because they are relatively expensive, they may be considered most suitable for providing water for a large population. Small commercial units provide about 6 liters of water a day, or 2,000 liters a year.[87] Large commercial units can provide between 100,000 and 4,000,000 liters a day.[88]

Cost

Commercial distillation units vary in price depending on scale and the price of electricity in the area where they are used. A small-scale commercial unit providing 2,000 liters of water a year costs about US$130, plus the cost of electricity.[89] A large commercial unit providing 4,000,000 liters per day requires about US$10,000 in capital costs, US$1,612 a year in maintenance and operating costs, and US$2,860 a year for energy. Places that have the technology to fabricate power plant equipment can also locally manufacture the parts needed for these desalination plants.[90] The cost of a homemade distillation unit is limited to acquiring the two pots and the fuel for the fire or stove used to heat them. The homemade unit can be placed on top of pots used for cooking in order to conserve fuel.[91] The cost of a solar still also varies depending on scale. Assuming use in a typical rural area and accounting for the cost of making the still, including the glass, wood, and concrete, and the cost of the land, operation, and repairs, a still may initially costs US$80 to $115 per square meter, or per 5 liters of water a day. Such a still will typically have a life of 20 to 30 years. The high price of land in urban areas may make solar stills prohibitively expensive for use in those areas.[92] New technological developments continue to make distillation equipment cheaper, more efficient, more durable, and able to operate at lower temperatures, decreasing the amount of energy needed. [93]

Ease of Use

Commercial distillation units do not require regular replacement parts unless combined with filter technology. Trained workers are required for maintenance which includes repairing structural damage and inspecting pumps. Over time, these units can become clogged with heavy metal buildup that requires a trained technician for removal with acid or a descaling agent. Countries that have the resources and ability to locally produce the parts needed for commercial distillation units will also require trained engineers and technicians for these processes. [94] Homemade distillation is considered to be simple to conduct and can be combined with other cooking activities. Knowledge and skill are also needed to design and build effective and efficient solar stills. Unskilled workers are also required for collecting feed water and distributing treated water.[95]

Additional Considerations

Large-scale distillation technology has been in use in Latin America, the Caribbean, the Middle East, and North Africa, and many Latin American countries have signed licensing agreements with foreign desalination manufacturing companies as a part of government policy. Field studies indicate that community level acceptance of commercial distillation is limited by the perception that the technology is overly high-tech and expensive. [96] Additionally, all distilled water may face consumer rejection because it has a stale taste.[97]

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[85] Doulton.
[86] The Schumacher Centre for Technology & Development, "Technical Brief - Solar Distillation," Rugby, UK, p. 4, <http://www.itdg.org/docs/technical_information_service/solar_distillation.pdf>.
[87] Johnson.
[88] United Nations Environment Programme - International Environmental Technology Centre, Source Book of Alternative Technologies for Freshwater Augmentation in Latin America and the Caribbean, Washington, DC, 1997, Chap. 2.2, "Desalination by distillation," <http://www.oas.org/dsd/publications/Unit/oea59e/ch21.htm>.
[89] Johnson.
[90] UNEP-IETC, Chap. 2.2. Latin American countries are specifically cited as having the potential to produce the equipment needed for desalination plants.
[91] Michael Smith and Rod Shaw, *Running Water: More Technical Briefs of Health, Water, and Sanitation*, Intermediate Technology Publications, London, UK, 1999, Brief 40, p. 32, <http://www.lboro.ac.uk/well/resources/technical-briefs/40-desalination.pdf>.
[92] The Schumacher Centre, p. 4.
[93] UNEP-IETC, Chap. 2.2.
[94] UNEP-IETC, Chap. 2.2.
[95] The Schumacher Centre, p. 2.
[96] UNEP-IETC, Chap. 2.2.
[97] Doulton.

I.4.3 Adsorptive Filter Media for Arsenic Removal

Ion exchange resins, activated alumina, and ferric oxide are three adsorptive filter media that are effective for the removal of arsenic and fluoride on a household or community scale. The filters take the form of columns, most often made of plastic pipes, which are filled with granules of the adsorptive media. These filters are often combined with other technologies to form water treatment systems that remove other contaminants from water as well. Ion exchange uses positively charged polystyrene-based resins to remove negative charged arsenic ions. Activated alumina has very high internal surface area which provides a large number of sites for adsorption. Granular ferric oxide is an iron-based adsorbent that can remove all forms of arsenic.

Contaminant Removal

All three technologies are generally able to remove more than 95 percent of arsenic from water, though all three also have limitations. If sulfate ions are also present in the water, ion exchange resins will preferentially remove those ions, leaving fewer bonding sites for arsenic ions. Activated alumina only works for water with a pH of 6 to 7, and ferric oxide is only effective below a water pH of 7.[98] Additionally, activated alumina filters require regular cleaning with an acid regenerant, after which their capacity is decreased by 30 to 40 percent.[99] Ion exchange and activated alumina treatment may both require pre-treatment if the water has high iron or manganese levels.[100] In addition to arsenic, iron exchange resins are able to remove almost all inorganic contaminants.[101]

Amount of Water Treated

Absorptive arsenic removal technologies are available for household, community, and municipal applications. Tetratreat®, a popular ion exchange resin technology, can provide water for 50 to 100 people, though it can be scaled both up and down.[102] A household activated alumina arsenic removal unit developed by the Bangladesh University of Engineering and Technology (BUET) that also combines flocculation-coagulation and filtration is designed to provide 40 to 50 liters of water per day, the amount estimated to be sufficient for a family's drinking and cooking.[103] Alcan Chemicals in Canada offers a household model and a community model of its activated alumina technology. The household model is designed for a family of 4 to 5, but can provide up to 1,000 liters of water a day at a flow rate of 60 to 90 liters per hour. The community model can serve up to 100 families at a flow rate of 300 liters per hour.[104] The Technical University of Berlin developed a granular ferric hydroxide adsorbent called AdsorpAs® that can be scaled up from a base 240 liters per hour to provide water for small rural communities or large towns with community waterworks.[105]

Cost

The Tetratreat® system costs about US$188 and has a life of 30 to 40 years. Other costs include salt needed for regeneration after every 30,000 liters of water treated.[106] The household activated alumina arsenic removal unit developed by BUET costs US$20, but is estimated to cost less once mass produced.[107] Alcan's activated alumina systems cost about US$28 for the household model and US$330 for the community model.[108] Several filters containing activated alumina and a composite of metal oxides are also available now and have been shown to be effective for arsenic removal and more cost-effective than pure activated alumina.[109] The AdsorpAs® granular ferric hydroxide system costs US$4,250 for a system designed to serve 20 to 80 households.[110]

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[98] Lance Frazer, "Metal Attraction," *Environmental Health Perspectives*, Vol. 13, No. 6, June 2005, p. 399.

[99] M. Feroze Ahmed, "An Overview of Arsenic Removal Technologies in Bangladesh and India," *Technologies for Arsenic Removal from Drinking Water,* Bangladesh University of Engineering and Technology, Dhaka, 2000, p. 261, <http://www.unu.edu/env/Arsenic/Ahmed.pdf>.

[100] Richard Johnston and Han Heijnen, "Safe Water Technology for Arsenic Removal," *Technologies for Arsenic Removal from Drinking Water*, Bangladesh University of Engineering and Technology, Dhaka, 2000, p. 18, <http://www.unu.edu/env/Arsenic/Han.pdf>.

[101] "National."

[102] Arsenic Policy Support Unit (APSU), "Policy Paper on Bangladesh Response to Arsenic Contamination of Groundwater," April 2005, p. 125, <http://www.apsu-bd.org/draft_projects%20and_organsiations/ab-technologies/drannexb1.pdf>.

[103] M.A. Jalil and Farooque Ahmed, "Development of an Activated Alumina Based Household Arsenic Removal Unit," *Technologies for Arsenic Removal from Drinking Water*, Bangladesh University of Engineering and Technology, Dhaka, 2000, p. 134, <http://www.unu.edu/env/Arsenic/Jalil.pdf>.

[104] APSU, p. 122.

[105] APSU, p. 123.

[106] APSU, p. 125.

[107] Jalil, p. 143. Price is as of 2000.

[108] APSU, p. 122.

[109] Ahmed, p. 261. These activated alumina/metal oxide composite filters include those produced by Alcan's Enhanced Activated Alumina, Bangladesh University of Engineering and Technology's Activated Alumina, Project Earth Industries, Inc. USA's Arsenic Removal Units, and Apyron Technologies Inc.'s Arsenic Treatment Unit. These filters were field tested in different areas of Bangladesh.

[110] Susan Murcott, "Arsenic and Fluoride Removal - New Household Approaches for Addressing Chemical Contamination," *Household and Water Treatment and Safe Storage Network Bulletin*, Issue 2, World Health Organization, May 2005, p. 8, <http://www.who.int/household_water/resources/bulletin_2.pdf>.

Ease of Use

POU adsorption filters require maintenance and waste disposal. Ion exchange resins require occasional regenerative cleaning using a brine solution. This cleaning process results in an arsenic-rich brine that requires specific disposal handling.[111] Activated alumina filters also require periodic cleaning with a regenerant such as alum or caustic soda, though they can operate for months before the media needs changing or regeneration.[112] Using the BUET activated alumina system involves pouring in the raw water, treating it with drops of pre-treatment chemicals, stirring, allowing it to sit, and then transferring it through the filtration unit.[113] The Alcan household model has a pour-through design and the community model is installed directly on the site of the tube well platform.[114] The AdsorpAs® system requires pouring water through a gravel filter and then a column filter filled with granular ferric hydroxide.[115] Appropriate spent waste disposal must be established and followed as well. The Tetratreat® system requires waste to be encapsulated in glass and then sealed in concrete for disposal.[116]

Additional Considerations

Field studies of the household activated alumina arsenic removal unit developed by BUET found that the technology was not well accepted by users who indicated that the unit was difficult to operate and did not operate properly, possibly because they had not been trained adequately to use the units.[117] The Alcan systems were found to be the most preferred POU arsenic removal technology by users in a field study.[118] Spent waste from the Alcan systems can be used for road construction or concrete latrine construction materials.[119]

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[111] Johnston, p. 18.
[112] Frazer, p. 399.
[113] Jalili, p. 134.
[114] APSU, p. 122.
[115] B.N. Pal, "Granular Ferric Hydroxide for Elimination of Arsenic from Drinking Water," *Technologies for Arsenic Removal from Drinking Water*, Bangladesh University of Engineering and Technology, Dhaka, 2000, p. 65, <http://www.unu.edu/env/Arsenic/Pal.pdf>.
[116] APSU, p. 125.
[117] Jalil, p. 143. Field studies were conducted in four areas of Bangladesh.
[118] David Sutherland, et al., "Rapid Assessment of Technologies for Arsenic Removal at the Household Level," *Technologies for Arsenic Removal from Drinking Water*, Bangladesh University of Engineering and Technology, Dhaka, 2000, p. 198, <http://www.unu.edu/env/Arsenic/Sutherland.pdf>. Field studies were between 2000 and 2001 in Bangladesh comparing nine different household arsenic removal technologies.
[119] APSU, p. 122.

[2] Nanotechnology-Based Water Treatment Technologies

The following section provides an overview of the types of nanotechnology applications that are relevant to water treatment. To illustrate each type of application, this section includes specific examples of innovations using nanotechnology. It should be noted, however, that many other specific nanotechnology-based products and approaches are being developed or may already be available. It should be noted that much of the information regarding these specific examples is based on public information provided by the manufacturers themselves. Since these products are not yet on the market or have not been on the market long, few independent studies exist regarding the performance of these products. Information about potential environmental or human health risks of these technologies is not included in this section because little, if any, data about these issues is available in the context of specific water treatment devices.

[2.1] Carbon Nanotube-Based Technologies

2.1.1 Carbon Nanotube Membranes

Carbon nanotubes can be uniformly aligned to form membranes with nanoscale pores that are able to filter out contaminants. Their nanoscale pores make these filters more selective than other filtration technologies. The carbon nanotubes also have high surface areas, high permeability, and good mechanical and thermal stability.[120] Though several other methods have been used, carbon nanotube membranes can be made by coating a silicon wafer with a metal nanoparticle catalyst that causes carbon nanotubes to grow vertically aligned and tightly packed. The spaces between the carbon nanotubes can then be filled with a ceramic material to add stability to the membrane. [121]

Contaminant Removal

Laboratory studies report that carbon nanotube membranes can remove almost all kinds of water contaminants, including turbidity, bacteria, viruses, and organic contaminants. These membranes have also been identified as promising for desalination and as an alternative to reverse osmosis membranes.

Amount of Water Treated

Although their pores are significantly smaller, carbon nanotube membranes have been shown to have the same or faster flow rates as much large pores, possibly because of the smooth interior of the nanotubes.[122]

Cost

The cost of producing carbon nanotube membranes continues to decrease as researchers develop new and more cost effective methods to mass produce carbon nanotubes. Some sources estimate that carbon nanotube membranes could become significantly less expensive than other filtration membrane technologies, including reverse osmosis membranes and ceramic and polymer membranes, as the price of carbon nanotubes falls.[123] Desalination using carbon nanotube filters could cost less than with reverse osmosis due to energy savings, since carbon nanotubes exhibit fast flow rate that reduce the amount of pressure needed to push water through. [124] Carbon nanotube membranes are expected to be more durable and easier to clean and reuse than conventional membranes without a decrease in filtering efficiency.[125]

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[120] A. Srivastava, et al., "Carbon nanotube filters," *Nature Materials*, Vol. 3, No. 9, September 3, 2004, p. 610.
[121] Aditi Risbud, "Carbon Drinking Water from the Ocean," *Technology Review*, June 12, 2006, <http://www.technologyreview.com/read_article.aspx?id=16977&ch=nanotech>.
[122] Risbud.
[123] Srivastava, p. 610.
[124] "Nanotube membranes offer possibility of cheaper desalination," Lawrence Livermore National Laboratory, Livermore, CA, June 5, 2005, <http://www.llnl.gov/PAO/news/news_releases/2006/NR-06-05-06.html>.
[125] Srivastava, p. 613.

Ease of Use
Carbon nanotube membranes could potentially be used in the same way as ultra- and microfiltration membranes. Studies indicate that they are durable, heat resistant, and easy to clean and reuse. These membranes can be cleaned through a process of ultrasonification and autoclaving at about 121 degrees Celsius for 30 minutes.[126]

Additional Considerations
Carbon nanotube desalination membranes are expected to reach the market in 5 to 10 years. Researchers are currently working to overcome challenges associated with scaling up the technology.[127]

2.1.2 Nanomesh

Seldon Laboratories, a small company in the U.S., has developed several device prototypes based on its nanomesh filter media. Nanomesh is composed of carbon nanotubes that are bound together and placed on a flexible, porous substrate. The nanotubes can be placed on a flat substrate to form a paper-like filter or on a rolled substrate that can be wrapped around any conventional cylindrical filter or other support structure. Flat nanomesh can also be pleated to maximize filter surface area.[128] Seldon currently has several portable water purification device prototypes based on this technology, most prominently a pencil-sized, straw-like filtration device known as the "waterstick."

Contaminant Removal
Seldon indicates that nanomesh can be engineered to remove a wide range of biological, organic, and inorganic contaminants. The filter media can be constructed of several layers of carbon nanotubes, with each layer functionalized to remove a different type of contaminant. Seldon says that the nanomesh currently used in the waterstick can be used to remove more than 99.99 percent of bacteria, viruses, cysts, spores, molds, coliform, parasites, and fungi and also significantly reduces lead and arsenic. Functionalized versions of nanomesh can remove organic contaminants such as pesticides and herbicides, as well as inorganic contaminants such as heavy metals, fertilizers, industrial effluents, and others. The filter media can also be coated with an antibacterial agent to prevent bio-film formation.[129] Seldon is currently working to enhance this technology so that it can be used to desalinate seawater.[130]

Amount of Water Treated
Seldon says that unlike other media with comparable pore size, nanomesh provides adequate flow rates without the application of pressure due to the fast mass transport properties of carbon nanotubes. A prototype filtration device with a 5 centimeter diameter has been shown to have a flow rate of 6 liters per hour.[131] The waterstick is designed to treat a liter of contaminated water within 90 seconds. It produces 200 to 300 liters of water during its useful life, though this can be extended by regularly changing the pre-filter.[132]

Cost
Seldon is planning to price the waterstick competitively with other similar technologies so that it will be affordable for people in developing countries, assuming aid organizations assist with distribution.[133]

Ease of Use
The waterstick is designed for individual use and is used like a drinking straw, producing clean water as the user drinks.[134] The waterstick is currently designed to be disposable, though Seldon indicates that, in time, it may develop a unit with replaceable filter cartridges. Additionally, the waterstick is designed to automatically stop flowing when its useful life is over.[135] Loose nanomesh media can be incorporated into existing filtration devices.[136]

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[126] Srivatava, p. 613.
[127] Risbud.
[128] Christopher H. Cooper, et al., "Nanomesh article and method of using the same for purifying fluids," United States Patent Application 20050263456, December 1, 2005.
[129] Cooper.
[130] "Seldon Laboratories In Windsor Adds Jobs With U.S. Contract Secured By Leahy, Jeffords," Office of Senator Leahy, May 12, 2005.
[131] "Nanomechanical Water Purification Device," NASA Small Business Innovation Research Proposal 03-A5.02-8173, 2003.
[132] Walter Derzko, "Smart Straws - The Waterstick & LifeStraw - a water nanofilter," October 20, 2005, <http://smarteconomy.typepad.com/smart_economy/2005/10/smart_straw_wat.html>.
[133] Derzko.
[134] Stefanie Olsen, "Tools for the ultimate high-tech survival kit," *CNET News,* September 30, 2005, <http://news.com.com/Tools+for+the+ultimate+high-tech+survival+kit/2100-11395_3-5885814.html>.
[135] Derzko.
[136] "Nanomechanical."

Additional Considerations
Seldon has reportedly developed a cost-effective mass production system for manufacturing nanomesh media.[137] Seldon's mass production system has a production capacity of 276 square meters of material per month, with each square meter providing enough material for 395 devices.[138] A water stick prototype is currently being used by doctors in Africa.[139]

[2.2] Other Nanofiltration Approaches

2.2.1 Nanofiltration Membranes and Devices

A number of nanofiltration membranes are available as alternatives to reverse osmosis and ultra- and microfiltration. For instance, Korean company Saehan Industries offers a line of nanofiltration membranes for use in a wide range of scales, including household POU. Additionally, Saehan has developed a device that incorporates nanofiltration with pre- and post-treatment filters for household water purification without the use of a storage tank. Storage water tanks are required for most reverse osmosis systems, but Saehan says that they can increase the risk of water recontamination if water is stored too long or with improper sanitation.[140]

Contaminants Removed
Saehan indicates that its nanofiltration device can be used to remove almost all water contaminants, including bacteria and heavy metals. Saehan says that the device is also effective for desalination because it removes 90 percent of ion contaminants and salts. [141]

Amount of Water Treated
The nanofiltration device can treat between 1 and 3.5 liters of water per minute. Amounts less than 1 liter are insufficient for the device to operate properly, and amounts in excess of 3.5 liters require the use of a larger pump to provide sufficient pressure.[142]

Cost
Saehan's smallest-scale nanofiltration membrane operates at 5 bars of pressure, while its smallest-scale reverse osmosis membrane produces 36 percent less water, but requires 55 bars of pressure.[143] Consequently, Saehan suggests that nanofiltration may be significantly less expensive than reverse osmosis because of its lower energy input needs.

Ease of Use
Use of the nanofiltration device involves pouring water into the entry spout and retrieving it from the exit spout when needed. Details on maintaining this system have not yet been released. Nanofiltration membranes are used in the same way as other similar membranes. These membranes must be stored in dry, room temperature conditions. They should not be exposed to excessive cold or heat. The membranes are sold in air tight bags to prevent bacterial growth, and, in the event that the bag is punctured, they should be placed in a replacement air tight cover. After initially used, the membrane should be kept wet at all times.[144]

Additional Information
Saehan's technology has been field tested in a variety of applications and locations, including drinking water treatment in China, desalination in Iran, and others.[145]

2.2.2 Nanofibrous Alumina Filters

U.S.-based Argonide Corporation offers nanofibrous adsorbent technology with its line of NanoCeram® filter media and cartridge filters, which are made with electropositive alumina nanofibers on a glass filter substrate. The alumina nanofibers

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[137] Matt Kelly, "Water filter wins Air Force deal for Seldon," *Mass High Tech: The Journal of New England Technology*, April 23, 2004, <http://masshightech.bizjournals.com/masshightech/stories/2004/04/26/story10.html>.
[138] Patrick O'Grady, "Windsor, Vt., Lab Applies for Grant to Make Water Purification Devices," *Eagle Times*, Claremont, New Hampshire, June 21, 2004.
[139] Olsen.
[140] Sung Ro Yoon, "Domestic nanofiltration membrane based water purifier without storage tank," US Patent 6,841,068, January 11, 2005.
[141] Yoon.
[142] Yoon.
[143] Saehan Industries, <http://www.saehancsm.com/>.
[144] Saehan.
[145] Saehan.

have more available surface area than conventional filter fibers and exhibit a higher electropositive charge, which Argonide indicates allows them to adsorb significantly more negatively charged contaminants such as viruses, bacteria, and organic and inorganic colloids at a faster rate.

Contaminant Removal

Argonide indicates that NanoCeram® filters remove and retain over 99.99 percent of viruses, bacteria, parasites, natural organic matter, DNA, and turbidity.[146] The filters have also been shown to adsorb 99.9 percent of salt, radioactive metals, and heavy metals such as chromium, arsenic, and lead, even the particles are nanoscale or dissolved.[147] NanoCeram® filters function best between pH 5 and 9.[148] Argonide offers a granular version of NanoCeram® that reportedly removes over 99 percent of salt, heavy metals, viruses, bacteria, and turbidity.[149]

Amount of Water Treated

Without the application of pressure, NanoCeram® filters have a flow rate of about 1 to 1.5 liters per hour per square centimeter of media. The maximum of 4 bars of pressure can be added, resulting in a flow rate of 9 to 10 liters per hour per square centimeter of media. [150] NanoCeram® cartridge filters have a pleated design that increases surface area, which gives them greater holding capacity.[151] The filter medium is also reported to be more clog resistant than ultraporous membranes.[152]

Cost

Argonide says that NanoCeram® filters are cheap to produce because they can be manufactured using papermaking technology.[153] The filter media currently cost US$10 per square meter, but may cost US$3 per square meter once mass produced.[154] Cartridge filters cost US$75 per 20 to 200 filters, depending on diameter.[155] Filter media sheets can be wrapped around a metal tube, placed between two conventional filters, or held in a screened container, minimizing the cost of acquiring a filter device.[156] Because NanoCeram® filters adsorb ultra-fine particles instead of collecting them on their surfaces, they have a relatively long useful life.[157]

Ease of Use

According to Argonide, NanoCeram® filters do not require pre- or post-treatment, cleaning, frequent filter changes, or hazardous waste disposal. Most set ups have a pour-through design.[158] The filters have been shown to simultaneously remove biological and chemical contaminants, even in salty of highly turbid water, without chemical disinfectants or coagulant-flocculants.

Additional Considerations

Argonide indicates that coolants and ultra-fine metal powders removed by NanoCeram® filters can be recovered and recycled for industry applications.[159]

2.2.3 Nanofiber Gravity-Flow Devices

U.S.-based KX Industries has developed World Filters, a line of gravity-flow filtration devices containing nanofibers specifically for use in developing countries. The filter medium consists of a prefiltration layer that removes dirt, an adsorption layer that removes chemical contaminants, and a nanofiber layer that removes colloidal-sized particles and contaminants. [160] The nanofiber medium is made from a variety of hydrophilic polymers, resins, and ceramics, cellulose, alumina, and other materials. The technology is available in household and community-level scales. [161]

[146] "NanoCeram® Fast-Flo Filters – Technical Data," Argonide Corporation, Sanford, FL, August 8, 2006, <http://www.argonide.com/technical.html>.
[147] Fred Tepper and Leonid Kaledin, "Nano Fiber Biological Filter," Argonide Corporation, Sanford, FL, <http://www.argonide.com/nanoceram_filters2.pdf>, pp. 2-3.
[148] "NanoCeram® Fast-Flo Filters – Technical Data."
[149] Fred Tepper (president of Argonide Corporation), "Nano Structured Arsenic Sorbent," presentation at the 2005 New Mexico Environmental Health Conference, Albuquerque, NM, November 1, 2005.
[150] "NanoCeram® Fast-Flo Filters – Technical Data."
[151] "NanoCeram® Filters," Argonide Corporation, Sanford, Fl, <http://www.argonide.com/presentation.pdf>.
[152] "NanoCeram® Fast-Flo Filters – Technical Data."
[153] "NanoCeram® Filters."
[154] Fred Tepper, et al., "High Performance Turbidity Filter," *Water Conditioning & Purification*, Vol. 47, No. 2, February 2005, p. 57.
[155] "NanoCeram® Fast-Flo Filters – Technical Data."
[156] "NanoCeram® Filters."
[157] "NanoCeram® Fast-Flo Filters – Technical Data."
[158] Tepper, "High," p. 57.
[159] "NanoCeram® Filters."
[160] Kevin McGovern (CEO of McGovern Capital LLC), presentation at Cornell University, Ithaca, NY, February 18, 2005.
[161] Evan E. Koslow, "Microporous filter media, filtration systems containing same, and methods of making and using," US Patent 6913154, June 5, 2005.

Contaminant Removal
World Filters reportedly remove over 99 percent of bacteria, viruses, parasites, organic contaminants, and other chemical contaminants.[162]

Amount of Water Treated
KX Industries indicates that the household scale World Filter device can produce 378 liters of water per filter at a rate of 4 to 6 liters per hour. The village-scale device produces more than 7,500 liters per day at a rate of 5.6 liters per minute. Each village scale filter is effective for up to 95,000 liters of water.[163]

Cost
The household device is expected to retail for US$6.00 to US$11.00, with replacement filters costing US$0.80 to US$0.90 each, translating to US$0.002 per liter of water. The village-scale device is expected to cost US$100 to US$150, which is approximately US$0.0003 per liter.[164]

Ease of Use
KX Industries indicates that World Filters are designed to be easy to use without training or extensive instructions. Both the household and village-level devices require no maintenance and have no moving parts.[165]

Additional Considerations
KX Industries plans to establish local facilities in developing countries for the production of the device hardware, as well as local distribution systems similar to those used by the beverage bottling industry. KX is also contracting NGOs to distribute the devices in some regions.[166]

[2.3] Nanoporous Ceramics, Clays, and Other Adsorbents

2.3.1 Nanoporous Ceramic Bio-Media Filtration

Pourous Ceramic Shapes, LLC, recently acquired by MetaMateria Partners in the U.S., offers a line of lightweight ceramic products with controlled porosity called Cell-Pore™, which is currently commercially available for treating water in fish tanks. The ceramic material hosts aerobic bacteria within its porous structure. These bacteria convert different pollutants into nontoxic substances.

Contaminant Removal
The aerobic bacteria hosted within the ceramic material reportedly convert organic pollutants and some harmful bacteria into non-toxic substances.[167] The ceramic can also be combined with nanoengineered reactants to remove phosphates, biological contaminants, heavy metals such as lead and arsenic, and other contaminants.[168]

Amount of Water Treated
Pourous Ceramic Shapes indicates that Cell-Pore™ has 100 times more available surface area than other comparable bio-media products. The ceramic material can also be used to support inorganic membranes as an alternative to reverse osmosis, which uses organic membranes.[169]

Cost
Ceramic filters are expected to become increasing cost-effective as rising oil prices drive up the cost of plastics used in organic and polymer membranes, filters, and substrates.[170] Porous Ceramic Shapes says that Cell-Pore's™ porosity prevents clogs in pre-filtration devices it might be combined with, reducing the costs associated with filter replacement.[171]

[162] Koslow.
[163] McGovern.
[164] McGovern.
[165] McGovern.
[166] McGovern.
[167] Cell-Pore, Inc., <http://www.cellpore.com/>.
[168] "MetaMateria Acquires Porous Ceramic Shapes Water Filtration Technology," AZoM, August 26, 2006, <http://www.azom.com/details.asp?newsID=6462>.
[169] "MetaMateria."
[170] "MetaMateria."
[171] Cell-Pore, Inc.

Ease of Use
Cell-Pore™ requires some maintenance, including allowing the aerobic bio-material to form within the material prior to use and, occasionally, scrubbing the filter's surface. Pourous Ceramic Shapes says that Cell-Pore's™ manufacturing process is flexible and a wide range of starting materials can be used for production.[172]

Additional Considerations
MetaMateria is planning to expand use of the material, as well as its manufacturing process, to drinking water treatment.

2.3.2 Nanoporous Ceramic Membrane Filter

Nanovation AG in Germany offers a line of nanoporous ceramic membrane filters under the name Nanopore® and membrane filtration systems with multiple filter modules. Nanopore® membrane filters are made from ceramic nanopowders on a support material such as alumina, and they are available in a variety of sizes and in two basic shapes: a tube-shaped round filter and a disk-shaped flat filter. These products are made using the company's proprietary ceramic nanopowders and continuous manufacturing process.

Contaminants Removed
Nanovation indicates that Nanopore® membrane filters effectively remove bacteria, viruses, and fungi from water.[173] Additionally, water quality tests did not find coliforms, fecal coliforms, salmonella, or streptococci in treated water.[174]

Amount of Water Treated
The amount of water provided by a Nanopore® membrane filter depends on its size and shape, as well as the quality of the water being treated. A filtration unit with dimensions of 120 by 60 by 15 centimeters provides 11 square meters of filter area and can treat 8,000 liters of wastewater per day.[175]

Cost
Nanovation says that Nanopore®-based membrane filtration systems can be produced inexpensively through a continuous manufacturing process that simultaneously assembles and fires all the layers of the filter. Nanopore® membrane filters are indicated to be cost competitive with polymer membranes when all the filtration process costs, including maintenance, replacement filters, cleaning agents, and operating costs, are combined, with these cost savings attributed to Nanopore® filters' longer life, greater durability, and less labor intensive cleaning process.[176]

Ease of Use
Nanopore® membrane filters and filtration systems require infrequent cleaning because of their strong anti-fouling properties. The membranes can also be steam sterilized, instead of chemically cleaned. Nanopore® membranes are resistant to bacterial and fungal decay, friction, concentrated acids and bases, high temperatures, and oxidation.[177]

2.3.3 Self-Assembled Monolayers on Mesoporous Supports (SAMMS™)

The U.S. Pacific Northwest National Laboratory (PNNL) has developed SAMMS™, a technology made from glass or ceramic materials with nanoscale pores to which a monolayer of molecules can be attached. Both the monolayer and the mesoporous support can be functionalized to remove specific contaminants. SAMMS™ have exhibited faster adsorption, higher capacity, and superior selectivity than many other membrane and sorbent technologies. SAMMS™ are designed for removing metal contaminants from drinking water, groundwater, and industrial waste streams.[178]

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[172] Cell-Pore, Inc.
[173] ItN Nanovation, 2006, <http://www.itn-nanovation.com>.
[174] Stig Botker, "Small-scale sewage plant tests ceramic flat membranes," *Water & Wastewater International*, Vol. 20, Issue 10, October 2005, <http://www.pennet.com/articles/article_display.cfm?article_id=241202>. Water quality tests were conducted on water treated by flat Nanopore® filters in a small sewage plant in Germany.
[175] Botker.
[176] ItN Nanovation.
[177] ItN Nanovation.
[178] "SAMMS - Technical Explanation of the Technology," Pacific Northwest National Laboratory, May 2006, <http://samms.pnl.gov/tech_descrip.stm>, accessed on August 29, 2006.

Contaminant Removal
PNNL indicates that SAMMS™ remove 99.9 percent of mercury, lead, chromium, arsenic, radionuclides, cadmium, and other metal toxins.[179] SAMMS™ can also reportedly be functionalized to remove specific metals or metal groups or not remove specific metals, such as calcium, magnesium, and zinc.[180] SAMMS™ are not effective for removing organic or biological contaminants.

Amount of Water Treated
SAMMS™ can reportedly be scaled for POU water treatment to industrial waste stream treatment. They provide 600 to 1,000 square meters of surface area for each gram of material.[181]

Cost
SAMMS™' reportedly costs US$150 per kilogram, compared to a typical ion exchange resin at US$42 per kilogram and activated carbon at US$1.78 per kilogram, and 13 kilograms of SAMMS™ are need to remove 1 kilogram of mercury, versus 154 kilograms of ion exchange resin and 40,000 kilograms of activated carbon.[182]

Ease of Use
SAMMS™ are available as powders and extrudates that can be retrofitted for ion exchange devices. SAMMS™ require occasional regeneration with an acid solution to remove the captured contaminants. Spent waste from SAMMS™ regeneration is considered nontoxic according to U.S. Environmental Protection Agency standards and can be disposed of as conventional waste.[183]

2.3.4 ArsenX

U.S. company SolmeteX, Inc. produces ArsenX™, an adsorbent resin made of hydrous iron oxide nanoparticles on a polymer substrate that is used for removing arsenic and other metal contaminants. The nanoparticles provide high surface area, large capacity, and rapid absorption kinetics. ArsenX™ can be scaled for small scale POU applications or large-scale industrial and community use, and it can also be used in existing devices designed for ion exchange resins.[184]

Contaminant Removal
ArsenX™ has been shown to remove arsenic, vanadium, uranium, chromium, antimony, and molybdenum. It does not remove sulfates, carbonates, fluoride, chloride, sodium, magnesium, or biological contaminants.[185]

Amount of Water Treated
ArsenX™ can be scaled for industrial, community, or household use. Flow rate depends mostly on the type of device in which ArsenX™ is being used. Regardless of system design, 2.5 to 3 minutes of contact time between ArsenX™ and the water is needed.[186] Each gram of ArsenX™ holds about 38 milligrams of arsenic.[187]

Cost
SolmeteX indicates that because it does not lose capacity during regeneration, ArsenX™ may cost less than other adsorbents over its life cycle.[188] The initial cost of the system depends on various different design considerations, but is reported to generally range from US$0.07 to $0.20 per thousand liters, including amortized capital costs and operation and maintenance costs.[189]

Ease of Use
SolmeteX says that ArsenX™ can be used the same way as ion exchange resins. It does not require pre- or post-treatment treatment or backwashing.[190] The material does require occasional regeneration with a mild caustic solution.[191] Depending on

[179] "'Mercury Sponge' technology goes from lab to market," Pacific Northwest National Laboratory," May 23, 2006, <http://www.pnl.gov/news/release.asp?id=159>.
[180] "SAMMS Technical Summary," Pacific Northwest National Laboratory, pp. 2-3, <http://samms.pnl.gov/samms.pdf>.
[181] "Nano-sponges for toxic metals," TerraDaily, November 12, 2005, <http://www.terradaily.com/reports/Nano_World_NanoSponges_For_Toxic_Metals.html>.
[182] "SAMMS Technical Summary," pp. 9-11.
[183] "SAMMS Technical Summary," pp. 7-9.
[184] "ArsenX^{np} Capabilities & Technical Specifications," SolmeteX, Inc, Northborough, MA, pp. 3, 6, <http://www.solmetex.com/pdfs/SOLArsenX_techspec.pdf>.
[185] "ArsenX^{np} Frequently Asked Questions," SolmeteX, Inc, Northborough, MA, <http://www.solmetex.com/aresenicfaq.html>.
[186] "ArsenX^{np} Frequently."
[187] Francis Boodoo, "ArsenX^{np} Nano-Particle Technology," presentation at the 2005 New Mexico Environmental Health Conference, Albuquerque, NM, November 2, 2005, <http://www.puroliteusa.com/ftp/Library/ArsenXnp%20NM%20Sandia%20Conf.pdf>.
[188] "ArsenX^{np} Capabilities," p. 5.
[189] Boodoo.
[190] "ArsenX^{np} Frequently."
[191] "ArsenX^{np} Capabilities," p. 5.

contaminant levels, ArsenX™ will be exhausted after 3 months to 1 year.[192] ArsenX™'s polymer substrate is reportedly durable and can operate in temperatures ranging from 1 to 80 degrees Celsius.[193]

2.3.5 Cyclodextrin Nanoporous Polymer

Cyclodextrin is a polymeric compound composed of particles with well-defined cylindrical cavities that can trap organic contaminants. Cyclodextrin polymer can be produced as a powder, granular beads, or thin film for use in different applications and devices. In addition to being used for POU water treatment, cyclodextrin polymer can also be used for *in situ* groundwater treatment or for cleaning oil and organic chemical spills.[194]

Contaminant Removal
Cyclodextrin has been shown to remove a range of organic contaminants, including benzene, polyaromatic hydrocarbons (PAHs), fluorines, nitrogen-containing contaminants, acetone, fertilizers, pesticides, explosives, and many others.[195] Tests indicate that cyclodextrin polymer reduces these contaminants to parts-per-trillion, versus activated carbon and zeolites, which reduce contaminants to parts-per-million. The polymer has also exhibited 100,000 times greater bonding with organic contaminants than activated carbon. The polymer has shown the same removal efficiency for water with low contaminant concentrations. Cyclodextrin polymer is not affected by air moisture and can be used in humid regions without becoming saturated and deactivated. It has also been shown to not leach the contaminants it has adsorbed.[196]

Amount of Water Treated
Cyclodextrin polymer has been shown to have a loading capacity of 22 milligrams of organic contaminant per gram of polymer, compared to 58 milligram per gram for activated carbon. It requires about 5 seconds of contact time with the contaminated water. Additionally, the material reportedly does not lose capacity from regeneration and can be reused indefinitely.[197]

Cost
Cyclodextrin polymer is reportedly cheap to manufacture and can be produced directly from starch with 100 percent conversion. Mass production is expected to bring the cost of cyclodextrin polymer below the price of activated carbon and zeolites.[198] Scientific Polymer Products, Inc. indicates that it has developed a method to scale this process for mass production of the material.[199] Manhattan Scientifics, Inc. is currently developing the technology for consumer applications and says that mass production will make the polymer less expensive than other organic contaminant removal methods.[200]

Ease of Use
Cyclodextrin polymer powder can be packed into column, cartridge, or bed filters through which water is passed, granular cyclodextrin can be placed directly in the water source or vessel, and thin film cyclodextrin can be placed on a glass substrate to form a membrane. All these different forms can be used in existing devices designed for filters, membranes, and adsorbents.[201] Since the cyclodextrin polymer material is both hydrophilic and hydrophobic, it can be used to draw water through the pores without the addition of pressure.[202] The polymer will need occasional regeneration using a simple alcohol such as ethanol or methanol. Cyclodextrin polymer may require more labor than activated carbon and other adsorbents because its loading capacity is lower.[203]

Additional Considerations
The contaminants absorbed by cyclodextrin polymer can be recycled after regeneration for fertilizers, pesticides, and various other industry products. [204]

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[192] Boodoo.
[193] Boodoo.
[194] Los Alamos National Laboratory, "Nanosponges Soak Up Contaminants and Cut Cleanup Costs," *Dateline Los Alamos*, April 1998, pp. 1, 3.
[195] Min Man and DeQuan Li, "Cyclodextrin Polymer Separation Materials," U.S. Patent Application 20010008222, July 19, 2001.
[196] LANL, p. 2.
[197] Man.
[198] LANL, p. 4.
[199] "Manhattan Scientifics Acquires Exclusive Option on World Rights to Patented Water Purification Technology," Manhattan Scientifics, Inc., March 21, 2000, <http://www.mhtx.com/media_center/pressrelease19.htm>.
[200] "Manhattan Scientifics to Acquire Los Alamos Labs' Ultra-Efficient Water Filter Technology for Consumer Use," Manhattan Scientifics, Inc., September 15, 1999, <http://www.mhtx.com/media_center/pressrelease10.htm>.
[201] Man.
[202] LANL, p. 3.
[203] Man.
[204] Man.

2.3.6 Polypyrrole-Carbon Nanotube Nanocomposite

The U.S. Pacific Northwest National Laboratory has developed a nanocomposite membrane made with a thin film of an adsorbent polymer called polypyrrole on a matrix of carbon nanotubes, which add surface area and stability to the membrane. Unlike other adsorbent products that require chemical regenerants, these membranes can be regenerated electrically.

Contaminants Removed
Polypyrrole-carbon nanotube membranes that are positively charged and can remove perchlorate, cesium, chromium, and other negatively charged contaminants.[205] The nanocomposite membrane can also be designed to remove salt.[206] The polypyrrole can also be negatively charged so that it removes positively charged particles such as calcium and magnesium.[207]

Amount of Water Treated
The polypyrrole-carbon nanotube nanocomposite membrane is reusable and tests have shown that the membranes lose very little effectiveness after 100 use cycles. These membranes have also exhibited rapid flow rates because of the fast mass transport properties of the carbon nanotubes.[208]

Cost
Polypyrrole-carbon nanotube membranes are expected to be relatively low-cost, especially with long-term use, because they can be regenerated and repeatedly used without significant loss in adsorptive capacity. These membranes may save on costs associated with purchasing and storing regenerative chemicals, disposal, and chemical handling training. Additionally, the cost of carbon nanotubes is expected to decrease by a factor of 10 to 100 in the next 5 years.[209]

Ease of Use
Polypyrrole-carbon nanotube membranes are expected to be moderately easy to use because they do not require chemical regeneration or handling of hazardous secondary waste. The adsorbed contaminants are released from the membrane by applying an electrically current to neutralize the charge of the polymer. Once the contaminants are removed, the polymer can be recharged and reused.[210]

Additional Considerations
Pacific Northwest National Laboratory's operating company, Battelle, has made this technology available for licensing and joint-research projects.[211]

[2.4] Zeolites

2.4.1 Natural, Synthetic, Coal Fly Ash, and Compound Zeolites

Zeolites are adsorptive materials with lattice-structures that form pores. They can be acquired from natural sources or fabricated in laboratories. Synthetic zeolites are usually made from silicon-aluminum solutions or coal fly ash, and are used as sorbents or ion exchange media in cartridge or column filters.[212] AgION Technologies, Inc. in the U.S. produces a compound made from zeolites and naturally-occurring silver ions that exhibits antibacterial properties.

Contaminant Removal
Zeolites are generally used for the removal of metal contaminants. Natural zeolites from Mexico and Hungary have been shown to reduce arsenic from drinking water sources to levels deemed acceptable by the World Health Organization.[213] Zeolites made from coal fly ash can adsorb a variety of heavy metals including lead, copper, zinc, cadmium, nickel, and silver from wastewater. Under some conditions, fly ash zeolites can also adsorb chromium, arsenic, and mercury. The adsorptive

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[205] Pacific Northwest National Laboratory, "Carbon nanotubes offer 'green' technology for perchlorate removal," July 25, 2006, <http://www.physorg.com/news73064933.html>.
[206] Yuehe Lin, "Electrically Controlled Anion Exchange Based on Polypyrrole and Carbon Nanotubes Nanocomposite for Perchlorate Removal," *Environmental Science and Technology*, Vol. 40, No. 12, June 15, 2006, p. 4006.
[207] Lin, p. 4004.
[208] Lin, pp. 4005-4006.
[209] Lin, pp. 4004-4005.
[210] PNNL.
[211] PNNL.
[212] LANL, p. 2.
[213] M.P. Elizalde-Gonzalez, et al., "Application of natural zeolites for preconcentration of arsenic species in water samples," *Journal of Environmental Monitoring*, Vol. 3, No. 1, 2001, p. 22.

capacity of zeolites is influenced by several factors including their composition, the water pH, and the concentrations and types of contaminants. For example, the water's pH influences whether the ash surface is positively or negatively charged. Also, because lead and copper are more easily adsorbed by fly ash, high concentrations of these metals decreases the amount of cadmium and nickel removed. [214] AgION's zeolite-silver compound has been proven effective against microorganisms, including bacteria and mold. Additionally, the silver in this compound provides residual protection against regrowth of these biological contaminants.[215] Zeolites do not adequately remove organic contaminants. Also, air moisture contributes to zeolites' saturation and makes them less effective.[216]

Amount of Water Treated
The amount of water that zeolites can treat depends on the zeolites' source and the device in which they are used. In the case of fly ash zeolites, the carbon content of the fly ash significantly influences surface area and, consequently, the adsorptive capacity of the zeolites.[217]

Cost
Zeolites can reportedly be produced cheaply because their source materials are naturally and abundantly available. In the U.S., zeolite granular media for industrial and agricultural applications costs US$30 to $70 per metric ton. For consumer products, it costs US$0.50 to $4.50 per kilogram.[218]

Ease of Use
The ease of use of zeolites depends mostly on the type of devices they are used in., which can include ion exchange resin, cartridge, and column devices, and others. Additionally, zeolites require occasional regeneration with an acid solution. Waste disposal handling and procedures are comparable to those for ion exchange resins. Disposal of fly ash zeolites may be problematic because studies have shown that trace amounts of lead, cadmium, chromium, copper, mercury, zinc, and other contaminants can be leached from the fly ash, causing water, groundwater, and soil contamination. Also, the levels of arsenic and manganese in fly ash leachate have previously been found to be higher than the levels recommended by the World Health Organization.[219] AgION's zeolite-silver compound requires infrequent cleaning because the silver antimicrobial coating prevents the build-up of biological contaminants on the filter. This also eliminates the need for storage, use, and disposal of chemical disinfectants. [220]

Additional Considerations
AgION's silver antimicrobial protection may be preferable to chemical disinfection because the microbes are less likely to develop resistance to silver.[221]

[2.5] Nanocatalyst-Based Technologies

2.5.1 Nanoscale Zero-Valent Iron

Nanoscale zero-valent iron (NZVI) is used for both *in situ* and *ex situ* treatment of contaminated groundwater. It functions simultaneously as an adsorbent and a reducing agent, causing organic contaminants to breakdown into less toxic simple carbon compounds and heavy metals to agglomerate and stick to the soil surface. NZVI can be injected directly into the source of contaminated groundwater as slurry for *in situ* treatment, or it can be used in membranes for *ex situ* applications. Bimetallic NZVI, in which the iron nanoparticles are coated with a second metal such as palladium to further increase the reactivity of the iron, is also available. NZVI is more reactive and has a large surface area than granular ZVI.

Contaminants Removed
NZVI can be used to treat a wide range of common environmental contaminants including chlorinated methanes, chlorinated benzenes, pesticides, organic dyes, trihalomethanes, PCBs, arsenic, nitrate, and heavy metals such as mercury, nickel, and silver. It may also be able to reduce radionuclides. Palladium coated NZVI has been shown to reduce all chlorinated compounds to

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[214] Jianmin Wang, "Characterizing the Metal Adsorption Capability of a Class F Coal Fly Ash," *Environmental Science and Technology*, Vol. 38, No. 24, December 15, 2004, pp. 6710-6711, 6714.
[215] "Battling bugs: new technologies provide safer water," *Appliance Design*, Vol. 54, No. 6, June 13, 2006.
[216] LANL, p. 3.
[217] Wang, p. 6710.
[218] Robert L. Virta, "Zeolites," *U.S. Geological Survey Minerals Yearbook - 2002*, Vol. I, 2002, <http://minerals.usgs.gov/minerals/pubs/commodity/zeolites/zeolmyb02.pdf>.
[219] Wang, p. 6710.
[220] "Battling."
[221] "Battling."

below detection levels in 8 hours, while regular NVZI achieved greater than 99 percent removal in 24 hours. [222] The nanoparticles remain active towards the contaminants for a period of 6 to 8 weeks. NZVI has been shown to be effective across a broad range of soil pHs, temperatures, and nutrient levels.[223] Competing anions, however, may reduce its effectiveness. Additionally, NZVI that is regenerated for reuse will corrode overtime and become less effective.[224]

Amount of Water Treated

The amount of groundwater that NZVI can treat may depend on the quality of the iron, including the number of times it has been reused, the type of substrate used (for *ex situ* use), and the quality of the water used to make the injectable slurry, including the amount of oxygen and the amounts and types of particulates in contains (for *in situ* use).[225] In one study, a 100 square meter area was effectively remediated with 6,057 liters of slurry containing 11.2 kilograms of NZVI.[226] Another study found that at one site 136 kilograms of NZVI was sufficient to treat 11.6 million kilograms of soil, while at another site the same amount of NZVI only treated 1.2 million kilograms of soil. Possible reasons cited for this disparity were the different volumes of water used in the preparation of the slurries, different levels of iron passivation due to differences in the waters' oxygen levels, and different amounts of pressure used during the injections.[227]

Cost

NZVI ranges from US$40 to $50 per kilogram.[228] Palladium-coated NZVI costs US$68 to $146 per kilogram. Though significantly more expensive than microscale and granular ZVI, which respectively cost US$2.20 to $3.75 per kilogram and US$0.88 per kilogram, NZVI reportedly may still be more cost effective because small amounts are needed due to its significantly greater surface area and reactivity.[229] NZVI has a reactive surface area of 33.5 square meters per gram, versus less than 1 square meter per gram for commercial ZVI powders, and allows for 10 to 100 times faster treatment rates.[230]

Ease of Use

NZVI is relatively easy to use both *in situ* and *ex situ*. For *in situ* remediation, NZVI powder is mixed with water in a tank to produce an iron slurry that is then injected with a pump and injection well directly into contaminated soil. No special well construction is necessary since the same equipment used for other injectable remediation is sufficient.[231] NZVI is reportedly easier to inject than granular ZVI because of its smaller particles, and it can achieve deeper subsurface penetration. NZVI nanoparticles can also be secured to a solid matrix of activated carbon, zeolites, carbon nanotubes, and others to produce membranes for *ex situ* remediation.[232]

2.5.2 Nanoscale Titanium Dioxide Photocatalysts

Titanium dioxide functions as both a photocatalytic reducing agent and an adsorbent, and it is used for both *in situ* and *ex situ* water treatment. In the presence of water, oxygen, and UV radiation, titanium dioxide produces free radicals that decompose a variety of contaminants into less toxic carbon compounds. Nanoscale titanium dioxide provides larger surface area and faster photocatalysis than larger titanium dioxide particles. Titanium dioxide is available in nanopowder form for use in suspensions or granular media filters. It is also available in several other forms, including, but not limited to, coatings for fixed membranes, nanocrystalline microspheres, and composite membranes with silica.

[222] Wei-xian Zhang, "Nanoscale iron particles for environmental remediation: An overview," *Journal of Nanoparticle Research,* Vol. 5, No. 3-4, August 2003, p. 326-328.
[223] National Science Foundation, "Nanoscale Iron Could Help Cleanse the Environment," NSF Office of Legislative and Public Affairs, Arlington, Va., September 3, 2003.
[224] Sushil Raj Kanel, et al., "Removal of Arsenic (III) from Groundwater by Nanoscale Zero-Valent Iron," *Environmental Science and Technology*, Vol. 39, No. 5, March, 1, 2005, p. 1297.
[225] Arun Gavaskar, et al., "Cost and Performance Report – Nanoscale Zero-Valent Iron Technologies for Source Remediation," Naval Facilities Engineering Service Center, Port Hueneme, Ca., August 29, 2005, p. 40.
[226] Zhang, p. 330. Slurry was made with potable water and had an iron nanoparticle concentration of 1.9 grams per liter. The field study was conducted in North Carolina, USA.
[227] Gavaskar, p. 38-40. Studies were conducted at the US Naval Air Station in Jacksonville, Florida and the US Naval Air Engineering Station in Lakehurst, New Jersey.
[228] NSF.
[229] Nancy E. Ruiz (Naval Facilities Engineering Service Center), "Use of Nano- and Micro-Scale Zero Valent Iron at Navy Sites: A Case Study," presentation given at the US EPA Workshop on Nanotechnology for Site Remediation, Washington, DC, October 20-21 2005.
[230] Neal Durant, et al. "Remediation of Perchlorate, NDMA, and Chlorinated Solvents Using Nanoscale ZVI," presentation given at the Remediation Technologies Development Forum Permeable Reactive Barriers Workshop, Niagara Falls, NY, October 16, 2003.
[231] Florin Gheorghiu et al., "In-Situ Treatments using Nano-Scale Zero-Valent Iron Implemented in North America and Europe," presentation given at the US EPA Workshop on Nanotechnology for Site Remediation. Washington, DC, October 20-21, 2005.
[232] Zhang, p. 324.

Contaminants Removed

Titanium dioxide breaks down almost all organic contaminants. It is also super-hydrophilic and, therefore, able to adsorb biological contaminants and heavy metals, including arsenic. Its effectiveness is influenced by the quality of the titanium dioxide, the UV intensity, the water's pH, the oxygen supply, and the concentration of contaminants.[233]

Amount of Water Treated

Different titanium dioxide systems provide different flow rates and speeds of removal, though all are generally reusable. Suspended titanium dioxide nanopowders provide the most efficient photocatalysis because their entire surface area is exposed for UV and contaminant contact. Titanium dioxide nanoparticles used as coating or fixed to glass, ceramic, or other substrates have been shown to exhibit 0.5 percent of the photocatalytic efficiency of suspended nanoparticles. This is due to a combination of reduced contact area and passivation from interactions with the support material. The porosity of the base membrane or substrate will also influence the flow rate and useful life of these systems. Titanium dioxide nanocrystalline microspheres have a surface area that is comparable to nanopowders, but slower photocatalysis.[234]

Cost

Titanium dioxide nanopowders cost several hundred dollars per kilogram, depending on quality. Altair Nanotechnologies, Inc. in the U.S., for instance, has recently patented a production system that they indicate can produce tonnage quantities of titanium dioxide nanopowder very inexpensively. Altair also plans to sell small-scale production units based on this technology. These production units will be available in two sizes, 40 kilograms per hour and 1 to2 kilograms per hour. The units produce titanium dioxide from titanium tetrachloride, which can be bought for about US$1,100 per metric ton, or US$1.10 per kilogram.[235]

Ease of Use

Suspended titanium dioxide nanopowders can be complicated to use because recovering or separating out the particles after the treatment is difficult. Suspended particles are usually separated through ultra- or microfiltration, but a significant amount of the powder can be lost during this process.[236] Nanocrystalline microspheres are easier to use. They are suspended in water by air bubbling and naturally sink to the bottom of the vessel or body of water for easy recovery.[237] Membranes and granular media filters that are coated, filled, or made with titanium dioxide will have similar ease of use as the base technology.

2.5.3 Titanium Oxide Nanoparticle Adsorbent

Adsorbsia™GTO™ is a granular adsorptive media from Dow Chemical Company that removes arsenic from water through the combined oxidative and adsorptive properties of titanium oxide. It is designed for small and mid-sized systems or POU applications.

Contaminants Removed

Dow indicates that Adsorbsia™ can be used to remove arsenic across a range of water pH and conditions. Under typical conditions, Adsorbsia™ has been shown to remove 12 to 15 grams of arsenic (V) and 3 to 4 grams of arsenic (III) per kilogram of media.[238] In addition to pH, removal efficiency is also not affected by the presence of sulfate, phosphate, iron, chlorine, or other anions in the water.[239] Since it is not affected by chlorine, Adsorbsia™ can be combined with disinfection to eliminate biological contaminants. Removal efficiency may be affected, however, by the amount of arsenic that is present in the water, the ionic form of the arsenic, competing impurities and ions, and the design of the equipment.[240] Additionally, Adsorbsia™ has not demonstrated any contaminant leaching or reverse arsenic reaction.[241] Adsorbsia™ is also said to remove viruses and bacteria.[242]

[233] X. Z. Li et al., "Photocatalytic Oxidation Using a New Catalyst – TiO_2 Microspheres – for Water and Wastewater Treatment," *Environmental Science and Technology*, Vol. 37, No. 17, September 1, 2003, p. 3992.
[234] Li, pp. 3989, 3992.
[235] Dirk Verhulst, et al. "A New Process for the Production of Nano-Sized TiO_2 and other Ceramic Oxides by Spray Hydrolysis," Altair Nanomaterials, Inc., Reno, NV, 2003, pp. 7-8.
[236] Haiman Zhang, et al. "Fabrication and Characterization of Silica/Titania Nanotubes Composite Membrane with Photocatalytic Capability," *Environmental Science and Technology ASAP Articles,* August 30, 2006, p. A.
[237] Li, p. 3994.
[238] "Introducing Cost-Effective Arsenic Removal You Can Count On," Dow Chemical Company, November 2005, p. 3.
[239] Alan Greenberg, "Adsorbsia™ Arsenic Removal Media – Properties and Performance," Dow Liquid Separations, May 10, 2006, p. 19.
[240] "ADSORBSIA GTO Media - Capacity," Dow Chemical Company, <http://dow-water.custhelp.com/cgi-bin/dow_water.cfg/php/enduser/std_alp.php?>.
[241] Andrew Clayton Baumgardner, "Arsenic Removal Using Titanium Dioxide Agglomerated Nanoparticle Adsorbents," master's thesis, Arizona State University, Tempe, Az., December 2005, p. 10.
[242] United Nations, "Bangladesh Water Purification Project Demonstrates Importance of Dow's 'Human Element'," Dow Chemical Company, July 25, 2006, <http://news.dow.com/dow_news/corporate/2006/20060725c.htm>.

Amount of Water Treated
Dow says that Adsorbsia™, because of its nanocrystalline form, exhibits ten times faster kinetics than iron media, allowing for faster flow rate.[243] The media is designed to operate with flow rates of 40 to 400 liters per minutes per square meter of media.[244] The quantity of water that the media can filter in its useful life depends on the source water quality and the system design.[245] Laboratory testing has found that Adsorbsia™ granule-filled column filters with a volume of 29 cubic centimeters and a flow rate of 1.3 liters per hour can produce between 25 and 38 liters of water per gram of dry granules before losing effectiveness.[246]

Cost
Adsorbsia's™ base price is US$14 per cubic decimeter of media, with lower pricing for larger quantities.[247] Because the costs of conventional technologies rise significantly as water systems become smaller, Adsorbsia™ is designed to be cost-effective for small and medium sized systems.[248] Adsorbsia™ does not have costs associated with purchasing and storing chemicals because it does not require regeneration. Adsorbsia™ is also safe for landfill disposal under current U.S. Environmental Protection Agency standards which Dow Chemicals indicates eliminates hazardous waste disposal costs.[249]

Ease of Use
According to Dow, Adsorbsia™ is designed to be compatible with existing system designs. The media can be used in existing devices designed for other granular media, sand, activated carbon, activated alumina, and others.[250] The media was also developed to be disposable in order to eliminate potentially difficult or labor intensive processes such as regeneration and hazardous waste disposal.[251] When the media is past its useful life, it can be removed and replaced with fresh media, though the use of a dust mask and safety glasses is recommended for transferring the dry media.[252] Unused media can be stored in dry conditions and is not affected by extreme cold or heat.[253] Backwashing may be needed periodically depending on feed water particulate levels and the system design.[254]

Additional Considerations
Dow Chemical Company has distribution routes throughout North America, South America, Europe, Asia, and the Pacific.[255] Adsorbsia™ has been field tested in Bangladesh.[256]

2.5.4 Nanostructured Iron Oxide Adsorbent

Adedge Technologies, Inc. in the U.S. offers AD33, a dry, granular nanostructured iron oxide media for removal of arsenic. AD33 combines the catalytic and adsorptive properties of iron oxide to breakdown arsenic into less toxic by-products and simultaneously filter it out of water. Adedge also offers a line of POU devices containing the AD33 media.[257]

Contaminants Removed
AD33 has been shown to remove over 99 percent of arsenic. It can also reduce levels of lead, zinc, chrome, copper, and other heavy metals.[258] AD33 has been shown to not leach adsorbed contaminants.[259]

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[243] Greenberg, p. 20.
[244] "ADSORBSIA GTO Media - Recommended Flow Rates," Dow Chemical Company, <http://dow-water.custhelp.com/cgi-bin/dow_water.cfg/php/enduser/std_alp.php?>.
[245] ADSORBSIA GTO Media - Projected Useful Life," Dow Chemical Company, <http://dow-water.custhelp.com/cgi-bin/dow_water.cfg/php/enduser/std_alp.php?>.
[246] Baumgardner, p. 69-70.
[247] Karen B. Laustsen (president, Aquacell Water Inc.), telephone conversation, September 6, 2006.
[248] Greenberg, pp. 4-5.
[249] "Aquacell chooses Dow's Adsorbia titanium-based arsenic removal media," *WaterWorld*, April 6, 2006, <http://www.pennnet.com/Articles/Article_Display.cfm?ARTICLE_ID=252180&p=41>.
[250] "ADSORBSIA GTO Media - Replacement for Existing Media," Dow Chemical Company, <http://dow-water.custhelp.com/cgi-bin/dow_water.cfg/php/enduser/std_alp.php?>.
[251] Greenberg, p. 8.
[252] "Adsorbsia™ GTO™ Arsenic Removal Media – Loading and Start Up Procedures," Dow Chemical Company, p. 1.
[253] "ADSORBSIA GTO Media - Storage Conditions," Dow Chemical Company, <http://dow-water.custhelp.com/cgi-bin/dow_water.cfg/php/enduser/std_alp.php?>.
[254] "ADSORBSIA GTO Media – Backwashing," Dow Chemical Company, <http://dow-water.custhelp.com/cgi-bin/dow_water.cfg/php/enduser/std_alp.php?>.
[255] "Introducing," p. 4.
[256] United Nations.
[257] "Arsenic is a major concern for both drinking water and household water," Water Testing Service and Laboratory, Inc., <http://wtsgroup.com/arsenic.html>.
[258] "Introducing the Medallion Series from Adedge," Adedge Technologies, Inc., February 2003.
[259] "Arsenic."

Amount of Water Treated
AD33 media typically has a useful life of 2 to 4 years.[260] Adedge's Medallion Series household treatment systems are available with three flow rates: 19, 26, and 38 liters per minute.[261] Adedge also offers filter cartridges containing AD33 with an average flow rate of 2 liters per minute. These cartridges have a useful life of 3,800 to 11,400 liters, which is estimated to be 4 to 6 times longer than other commercially available adsorption products. [262]

Cost
Adedge says that its Medallion Series products are reportedly comparable to anion exchange products in cost.[263] AD33 filter cartridges cost about US$50 each.[264] The cost of loose media depends on the quantity purchased, but typically ranges between US$8 and $13 per liter.[265]

Ease of Use
According to Adedge, AD33 media and products require infrequent replacement, and do not require the use of chemicals or regenerants. Because it is dry, AD33 media is reportedly easier to handle than wet iron-based filtration media and can also be used in a broader range of system types. Additionally, spent AD33 media is not hazardous and can be landfilled according to U.S. Environmental Protection Agency standards.[266] The media can be used in any standard granular media device with a downflow configuration. Such devices will require twice monthly backwashing to maintain their flow rate. [267] Medallion Series systems are prepackaged and automatically conduct preprogrammed backwashing.[268]

[2.6] Magnetic Nanoparticles

2.6.1 MagnetoFerritin

Magnetic nanoparticles are generally studied as adsorbents and nanocatalysts for water treatment. NanoMagnetics, Ltd., a U.K. company, has developed a magnetic nanoparticle called MagnetoFerritin and is studying its ability to enable forward osmosis, a potentially energy efficient alternative to reverse osmosis. Magnetic nanoparticles would be used in such a system to produce the osmotic pressure needed to pull water through a filtration membrane, unlike reverse osmosis that requires energy-input to produce osmotic pressure.[269]

Contaminants Removed
MagnetoFerritin-enabled forward osmosis is intended for desalination, though other contaminants can also be removed, depending on the type of membrane that is used.

Amount of Water Treated
Nanomagnetics says that MagnetoFerritin can be recovered from the purified water and reused without any specific limit.

Cost
Specific cost information for MagnetoFerritin is not available, but NanoMagnetics indicates that the long life and reusability of the material makes it more cost effective than reverse osmosis. Forward osmosis also eliminates energy-related costs, which account for 40 percent of the cost of reverse osmosis.

Ease of Use
A precise system for MagnetoFerritin has not yet been designed, but sources indicate that the magnetic nanoparticles would be added to some clean "draw" water on one side of a membrane to create a concentration imbalance with the source water. This difference in concentration would create the osmotic pressure needed to pull the source water through the filter. The nanoparticles could then be recovered from the purified water using a magnetic field.

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[260] "Arsenic."
[261] "Introducing."
[262] "POU Cartridge for Arsenic," Adedge Technologies Inc, <http://adedgetechnologies.com/LiteratureSource/2710S_4510S.PDF>.
[263] "Introducing."
[264] "POU."
[265] Sales Representative (Adedge Technologies), telephone conversation, September 9, 2006.
[266] "Arsenic."
[267] "Point of Entry," Water Testing Service and Laboratory, Inc., <http://wtsgroup.com/ptentry.html>.
[268] "Introducing."
[269] "Nanomagnetics," UK Trade and Investment, <http://www.ukatnanofair.com/ex_nanomagnetics.html>.

[3] Comparative Charts of POU and Nanotechnology-Based Treatments

Table 3.1 Comparison of POU Water Filtration Technologies

Filter Type		Contaminants Removed: Biological	Contaminants Removed: Organic	Contaminants Removed: Inorganic	Amount of Water: Flow Rate	Amount of Water: Useful Life	Cost (US$): Unit	Cost (US$): Filter	Ease of use: Labor Demands	Ease of use: Set-Up & Use	Ease of use: Maintenance
Ceramic	Disk	• Bacteria • Cysts* • Coliform • Fecal Coliform	No	• Asbestos • Iron	1 - 11 L/hr	5 yrs	$3.50	$0.49 - $1.02	Unskilled	Easy	Monthly scrubbing
	Candle				0.3 - 0.8 L/hr	6-12 mos	$2.29	$0.46			
Biosand		• Coliform • Fecal Coliform • Protozoa • Helminthes	No	• Arsenic • Cadmium • Copper • Iron • Lead • Zinc	30 L/hr	Indefinite	$12.00 - $30.00	n/a	Unskilled	Moderate - biolayer must be established	Sporadic sand agitation and cleaning
Activated Carbon	Granular	• Bacteria • Cysts (bact. within the filter can cause recontamin.)	Most all, incl: • Pest-, Herb-, & Insecticides • Industrial Chemicals • PCBs • PAHs • VOCs • MTBE	• Arsenic • Chlorine • Chromium • Mercury (organic complex forms only)	V** - Unit size	9-12 mos	$100/yr $10-Carafe	$3.00	Unskilled & Trained	Easy	Regular cleaning by trained person
	Solid Block					12 mos	$330 - $2500	$0.02/L			
Granular Media	Bucket	• Bacteria • Cysts • Coliform • Parasites • Protazoa	No	No	500 L/day	V - Media	$50.00	$20.00	Unskilled	Easy	Biweekly filter cleaning
	Drum & Filter				40-200 L/day		<$0.001/L - $01/L	U*** - Low	Unskilled & Trained	Easy	Backwashing by trained person
	Roughing				V - Unit size		U - Low				
	Cistern								U		
Fiber & Fabric		• Pathogenic Larvae • Larva-Hosting Crustaceans • Bacteria with Large Copepods • Zooplankton	No	No	V - No. of material layers	Limited	≈ $0.00	≈ $0.00	Unskilled	Easy	None

* - Cysts: Giardia & Cryptosporidium Cysts
** - V: Variable depending on -
*** - U: Exact Amount Unspecified

Table 3.2 Comparison of POU UV Radiation and Chemical Treatment Technologies

Technology Type		Contaminants Removed: Biological	Contaminants Removed: Organic	Contaminants Removed: Inorganic	Amount of Water Treated: Flow Rate	Amount of Water Treated: Useful Life/ Chem. Quant.	Cost (US$)	Ease of use: Labor Demands	Ease of use: Set-Up & Use	Ease of use: Maintenance
UV Radiation	UV Lamps	• Bacteria • Bact. Spores • Coliform • Enteric Viruses	No	No	>1 L/min	1 yr/bulb	$10 - $100/yr	Unskilled	Easy	Regular cleaning
	Sodis				10 L/bottle	Indefinite	≈$0.00			Regular bottle cleaning
Coagulation - Flocculation	Synthetic Polymer	• Bacteria • Coliform • Fecal Coliform • Viruses	No	• Arsenic • Asbestos • Cadmium • Chromium • Selenium	n/a	V** - Source water quality	>$100/yr/hh***	Unskilled & Trained	Moderate - Trained person must determine necc. dosage	Chemical storage and preparation by trained person
	Alum & Iron Salt						$10 - $100/yr/hh			
	Natural Polymer						<$10/yr/hh		Moderate - Powder crushed before each use	n/a
Chemical Disinfection	Sodium Hypochlorite	• Bacteria • Coliform • Fecal Coliform • Viruses	No	No	n/a	25 mL/mo.	$700-$2500 - Generator $4.80-$9.60/yr/hh	Unskilled & Trained	Moderate - Trained person must generate chemical	Chemical storage and preparation by trained person
	Bleaching Powder						$10/yr/hh		Easy	
PuR® Flocculant-Disinfectant		• Bacteria • Cysts* • Coliform • Fecal Coliform • Parasites • Protozoa • Viruses	No	• Arsenic	10 L/sachet	n/a	$.10/sachet	Unskilled	Easy	None

* - Cysts: Giardia & Cryptosporidium Cysts
** - V: Variable depending on -
*** - HH: Household (4-5 people)

Table 3.3 Comparison of POU Desalination and Arsenic Removal Technologies

Technology Type		Contaminants Removed			Amount of Water Treated		Cost (US$)		Ease of use		
		Biological	Organic	Inorganic	Flow Rate	Useful Life	Unit	Filter	Labor Demands	Set-Up & Use	Maintenance
Reverse Osmosis	Portable	• Bacteria • Cysts* • Parasites • Viruses	• Pest-, Herb-, & Insecticides • MTBE • Chemical Effluents • VOCs (< recommended amounts)	Most all, incl: • Sea Salt • Arsenic • Asbestos • Cadmium • Chlorine • Copper • Fluoride • Iron • Lead • Nitrates & Nitrites	4 - 75 L/day	1-3 yrs per membrane	$200- $4000	U***	Unskilled	Easy	Occasional tank cleaning & filter replacement
Reverse Osmosis	Large-Scale				1,000 - 10,000 L/day	2-4 yrs per membrane	$3.50 - $12 per 1000L	U	Skilled	Difficult	Skilled person must monitor, inspect, calibrate, and repair system
Distillation	Solar Stills	No	No	Most all, incl: • Arsenic • Asbestos • Cadmium • Chromium • Copper • Fluoride • Iron • Mercury • Nitrates & Nitrites • Selenium	2.3 L/m² still	Indefinite	$80 - $115/m² still	n/a	Unskilled & Trained	Easy	Occasional repairs by trained person
Distillation	Homemade Units	• Bacteria • Cysts • Viruses			V** - Container size		≈$0.00	n/a	Unskilled	Easy	Regular cleaning
Distillation	Commercial Units				6 L/day - Sm. 100,000-4,000,000 L/day - Lg.		$100 - Sm. $10,000 - Lg.	$4500/yr - electricity & maintenance	Trained	Moderate	Trained person must maintain system
Adsorbent Filter Media	Ion Exchange Resins	No	No	Most all, incl: • Arsenic • Asbestos • Cadmium • Chromium • Copper • Fluoride • Iron • Mercury • Nitrates & Nitrites	30,000 L/regen.	U - some % capacity lost per regen.	$188	n/a	Unskilled & Trained	Moderate	Occasional regeneration & proper disposal of hazardous spent regen. Waste by trained person
Adsorbent Filter Media	Activated Alumina				40-50 L/day – BUET 1,000 L/day – Alcan Sm. 300 L/hr – Alcan Lg.	30-40% capacity lost per regen.	$20 - $330				
Adsorbent Filter Media	Ferric Oxide				>240 L/hr - AdsorbAS	U - some % capacity lost per regen.	$4,250				

* - Cysts: Giardia & Cryptosporidium Cysts
** - V: Variable depending on -
*** - U: Exact Amount Unspecified

Table 3.4 Comparison of POU Nanotechnology-Based Water Treatment Technologies

Technology Type		Contaminants Removed: Biological	Contaminants Removed: Organic	Contaminants Removed: Inorganic	Amount of Water Treated: Flow Rate/ Water Quantity	Amount of Water Treated: Useful Life	Cost (US$)*: Unit	Cost (US$)*: Filter/Media	Ease of use: Labor Demands	Ease of use: Set-Up & Use	Ease of use: Maintenance
CNT Membranes		Most all**	U****	• Sea Salt • Arsenic • Cadmium • Mercury • Selenium	U - > reverse osmosis membranes	U	U - 75% < reverse osmosis		Use comparable to reverse osmosis membranes Requires less frequent maintenance		
Nanomesh	Filters	Most all	• Pest-, Herb-, & Insecticides • Industrial Effluents (Almost all org. cont. can be removed through functionalizing the material)	• Arsenic • Lead (Almost all inorg. cont. can be removed through functionalizing the material)	6 l/hr - prototype	U	U - competitive		Unskilled	Easy	n/a
	Waterstick				0.67 L/min	200-300 L per stick	U -competitive	n/a			
Nanofiltration	Membranes	Most all	U	Most all	V - membrane size	U	U - <reverse osmosis		Use comparable to reverse osmosis membranes Requires less frequent maintenance		
	Devices				1 - 3.5 L/min	U			Unskilled	Easy	n/a
Nanofibrous Filters	NanoCeram	Most all	U	• Sea Salt • Arsenic • Chromium • Lead • Radionuclides • Other U	1 - 1.5 L/min/cm^3 media	U - 10X > other fiber filters	U- retrofitted	$3.00/$m^2$ media $75- 20-200 filters dep. on size	Unskilled	Easy	Infrequent cleaning
	World Filter	• Bacteria • Parasites • Viruses		U	4-6 L/hr – HH unit 336 L/hr – Village unit	378 L – HH unit 95,000 L per filter – Village unit	$6.00-$11 – HH unit $100-$150 – Village unit	$0.80 - $0.90			n/a

* - Costs assume mass production

** - Biological contaminants: Bacteria, Bacterial Spores, Giardia & Cryptosp. Cysts, Coliform, Fecal Coliform, DNA & RNA, Fungi, Mold, Parasites, Protozoa, and Viruses

Organic contaminants: Pest-, Herb-, & Insecticides, Industrial Effluents, MTBE, PAHS, PCBs, VOCs, and others

Inorganic contaminants: Heavy Metals, Nitrites, Salts, Asbestos, Radionuclides, Calcium, Magnesium, and others

*** - V: Variable depending on -

**** - U: Exact Amount Unspecified

Technology Type		Contaminants Removed			Amount of Water Treated		Cost (US$)*		Ease of use		
		Biological	Organic	Inorganic	Flow Rate/ Water Quantity	Useful Life	Unit	Filter/Media	Labor Demands	Set-Up & Use	Maintenance
Nano- Ceramics, Clays, and Adsorbents	Cell-Pore	• Bacteria	U	• Arsenic • Lead • Other U	U - 100X > other organic membranes	U	U- retrofitted	U - competitive	Unskilled	Moderate - biolayer must be established	Biweekly filter cleaning
	Nanopore	• Bacteria • Coliform • Fecal Coliform • Fungi • Viruses	U	U	V*** - source water quality and membrane size	U			Unskilled	Easy	Infrequent steam sterilization
	SAMMS	No	No	• Arsenic • Cadmium • Chromium • Lead • Mercury • Radionuclides • Other U	U - 13X > other adsorbents	Indefinite		$150/kg	Unskilled & Trained	Moderate	Occasional regeneration by trained person
	ArsenX	No	No	• Arsenic • Chromium • Molybdenum • Uranium • Vanadium	38 mg arsenic per gram media	Indefinite		$0.07- $0.20 per 1000L			
	Cyclodextrin Polymer	No	Most all	U	22 mg organ. contamin. per gram media	Indefinite		U - competitive			
	Polypyrrole Polymer	U	U	• Sea Salt • Calcium • Cesium • Chromium • Magnesium • Perchlorate • Other U	U	Indefinite			Trained	Moderate	Occasional regeneration with electrical current by trained person

* - Costs assume mass production

** - Biological contaminants: Bacteria, Bacterial Spores, Giardia & Cryptosp. Cysts, Coliform, Fecal Coliform, DNA & RNA, Fungi, Mold, Parasites, Protozoa, and Viruses

Organic contaminants: Pest-, Herb-, & Insecticides, Industrial Effluents, MTBE, PAHS, PCBs, VOCs, and others

Inorganic contaminants: Heavy Metals, Nitrites, Salts, Asbestos, Radionuclides, Calcium, Magnesium, and others

*** - V: Variable depending on -

**** - U: Exact Amount Unspecified

<table>
<tr><th colspan="2" rowspan="2">Technology Type</th><th colspan="3">Contaminants Removed</th><th colspan="2">Amount of Water Treated</th><th colspan="2">Cost (US$)*</th><th colspan="3">Ease of use</th></tr>
<tr><th>Biological</th><th>Organic</th><th>Inorganic</th><th>Flow Rate/ Water Quantity</th><th>Useful Life</th><th>Unit</th><th>Filter/Media</th><th>Labor Demands</th><th>Set-Up & Use</th><th>Maintenance</th></tr>
<tr><td rowspan="2">Zeolites</td><td>Coal Fly Ash</td><td>No</td><td rowspan="2">No</td><td rowspan="2">• Arsenic
• Cadmium
• Chromium
• Cooper
• Lead
• Mercury
• Nickel
• Zinc
• Other U</td><td rowspan="2">V- source water quality</td><td rowspan="2">U</td><td rowspan="2">U- retrofitted</td><td rowspan="2">$0.50- $4.50/kg</td><td rowspan="2">Unskilled & Trained</td><td rowspan="2">Moderate</td><td rowspan="2">Occasional regeneration and hazardous spent waste disposal by trained person</td></tr>
<tr><td>AgION</td><td>• Bacteria
• Mold
• Other U</td></tr>
<tr><td rowspan="5">Nanocatalysts</td><td>NZVI</td><td rowspan="2">No</td><td rowspan="2">Most all</td><td rowspan="2">• Arsenic
• Mercury
• Nickel
• Nitrates
• Silver
• Radioactive Metals
• Other U</td><td rowspan="2">V - source water quality and membrane size</td><td rowspan="2">U - some % capacity lost per regen.</td><td rowspan="5">U- retrofitted</td><td>$40- $50/kg</td><td rowspan="3">Trained & Skilled</td><td rowspan="3">Difficult</td><td rowspan="3">Maintenance must be conducted by skilled and trained persons</td></tr>
<tr><td>Pd-Coated NVZI</td><td>$68- $146/kg</td></tr>
<tr><td>Nano-Titanium Dioxide</td><td>Most all - U</td><td>Most all</td><td>• Arsenic
• Other U</td><td>V - membrane size</td><td>Indefinite</td><td>$1.10 - >$100/kg</td></tr>
<tr><td>Adsorbsia</td><td>• Bacteria
• Viruses</td><td>U</td><td>• Arsenic</td><td>40-400 L/min/m² filter</td><td>25-38 L/g media</td><td>$14/L media</td><td>Unskilled</td><td>Easy</td><td>n/a</td></tr>
<tr><td>AD33</td><td>U</td><td>U</td><td>• Arsenic
• Chromium
• Copper
• Lead
• Zinc
• Other U</td><td>16-38 L/min – systems

2 L/min - cartridges</td><td>2-4 yrs – media

3,800-11,400L - cartridges</td><td>$8 - $13/L media

$50 - cartridges</td><td>Unskilled</td><td>Easy</td><td>n/a</td></tr>
<tr><td colspan="2">Magnetoferritin</td><td colspan="3">V - dep. on membrane</td><td colspan="2">U</td><td colspan="2">U</td><td colspan="3">U</td></tr>
</table>

* - Costs assume mass production

** - Biological contaminants: Bacteria, Bacterial Spores, Giardia & Cryptosp. Cysts, Coliform, Fecal Coliform, DNA & RNA, Fungi, Mold, Parasites, Protozoa, and Viruses

Organic contaminants: Pest-, Herb-, & Insecticides, Industrial Effluents, MTBE, PAHS, PCBs, VOCs, and others

Inorganic contaminants: Heavy Metals, Nitrites, Salts, Asbestos, Radionuclides, Calcium, Magnesium, and others

*** - V: Variable depending on -

**** - U: Exact Amount Unspecified