extremely effective way to disinfect water, it has several disadvantages. The main disadvantage is that fuel is required to boil the water. This fuel can require significant time to gather and can also place additional stress on a region that is already experiencing deforestation. Additionally, using wood for fuel increases exposure to the environmental risk factor indoor smoke from burning of solid fuels. Also, water requires time to cool after it is boiled. Boiled water can have an unpleasant, “flat” taste, which can be improved by shaking the storage container to allow more air to enter the water.

Boiling is often recommended to treat water but is actually overkill because water does not need to reach 100 °C to be disinfected. However, bringing water to a rolling boil provides a built-in indicator that a sufficiently high temperature has been reached. If alternative indicators are available, water only needs to be treated to pasteurization temperatures. For example, *water pasteurization indicators* (WAPIs) are small devices filled with wax that melts at a certain temperature, which can tell users when water can be considered safe to use. Several recommendations exist as to the temperature that must be reached and the length of time that water must stay at that temperature. A conservative recommendation is that water should stay at 70 °C for 10–15 min (Laurent 2005). Figure 18-13 shows that at lower temperatures, water must be heated for longer periods of time. Water can be heated over a fire or by using a solar cooker as well (see www.solarcooking.org).

18.7.4 Solar UV Disinfection

Lower wavelengths of light disinfect water by inactivating the DNA of bacteria, viruses, and other pathogens (Gadgil and Shown 1995). In addition to the effects of direct absorption of the radiation by the bacteria, light radiation also produces reactive forms of oxygen that kill microorganisms. Ultraviolet light is most effective and is divided into three ranges: UV-A (315–400 nm), UV-B (280–315 nm), and UV-C (100–280 nm) (Gadgil and Shown 1995). The most lethal wavelength for destruction of pathogens is between 200 and 300 nm, so UV-C light is the best germicidal wavelength (Crittenden et al. 2005). A mercury lamp, similar to a fluorescent lamp, provides light of wavelengths around 254 nm, an appropriate range for destruction of germs, and this method is commonly used in drinking water treatment in developed countries.

In the case where electricity is expensive or unavailable, the next-best option may be to use solar radiation. Although the smallest wavelengths of radiation do not reach the earth, wavelengths in the UV-A range (also called the near-ultraviolet region) do reach the surface of the earth and have disinfection potential. Additionally, if the water temperature reaches 45 °C, synergy between UV radiation and temperature occurs, improving treatment. In fact, if the temperature exceeds 50 °C, the treatment process is three times faster (EAWAG 2002).

Solar disinfection (SODIS) is a simple treatment method that takes advantage of the bacterial destruction potential of sunlight. Treatment involves placing clear bottles of water to be treated in direct sunlight for a determined amount of time.

SODIS is mainly limited by the initial water quality and availability of clear and clean plastic bottles. In tropical regions, where daylight is consistent throughout the year,

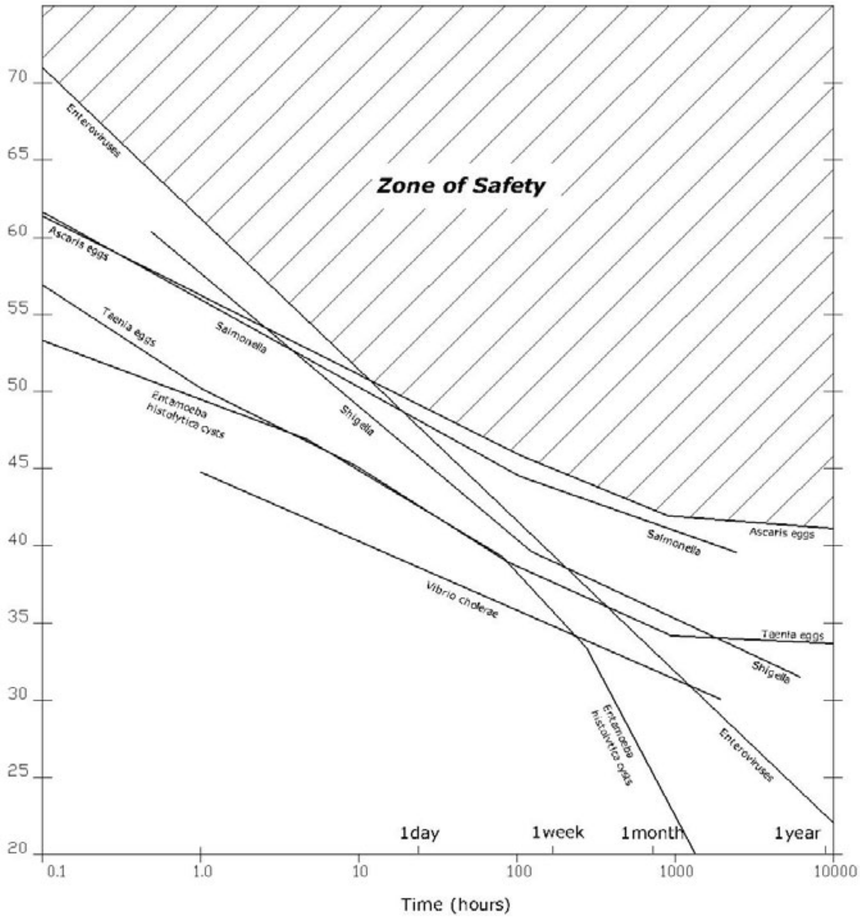

Figure 18-13. Required Temperatures for Complete Inactivation of Pathogens.

Source: Redrawn with permission of Cairncross and Feachem (1983).

light should not pose a problem. Even on 100% cloudy days, the method works with a longer exposure time. Regions between 15° N/S and 35° N/S are considered to be most favorable for solar disinfection because they generally have semiarid climates with little cloud cover. However, the region between the equator and 15° N/S is also favorable (EAWAG 2002). SODIS can be used for microbially contaminated water that has low turbidity (<30 NTU) and is free of chemical contamination (EAWAG 2002).

Because the most effective germicidal wavelengths are below the visible light range (<400 nm), clear glass or plastic bottles are the best option for solar disinfection. Clear containers transmit light in the near-ultraviolet range, as well as in the visible range. Another important factor is the material of the bottle. Glass and plastic are the only real options. The advantages to glass are that it is more resistant to scratching (which reduces light penetration), it has no photoproducts, and it is heat resistant.

Obvious disadvantages to glass are its ability to break, higher costs, and weight. Also, ordinary glass will not transmit UV-radiation if it is thicker than 2 mm. Pyrex, Corex, Vycor, and quartz glasses transmit UV-radiation significantly more than window glass. These types of glass are more costly than ordinary window glass. Plastic bottles are lightweight and less breakable, although less heat resistant (EAWAG 2002). Because they are also generally less expensive, plastic bottles seem to be the best option.

Plastic drinking bottles are either made of polyethylene terephtalate (PET) or polyvinyl chloride (PVC). Although both kinds of plastics contain additives like UV stabilizers, PET bottles contain fewer and so are chemically more stable (EAWAG 2002). In many places, plastic bottles are used for distributing commercial bottled water and are thus readily available for reuse, either sold as used bottles in markets or collected from individuals who consume bottled water.

The procedure for solar disinfection is as follows:

1. Use SODIS for water with no chemical contamination and with turbidity less than 30 NTU. Pretreat the water by filtration or sedimentation to remove turbidity.
2. Wash a 1–2-L PET bottle well the first time the bottle is used. Use four bottles per person, allowing two bottles to be used for consumption and two bottles to be used for treatment.
3. Fill the bottle 75% full of water to be treated, cover it, and shake it for 20 s to aerate the water and increase the dissolved oxygen. Higher oxygen content results in more efficient disinfection because disinfection results from oxygen free radicals and hydrogen peroxides that are produced by the sunlight in water. EAWAG recommends, however, that aeration only take place at the beginning of the SODIS process because continuous shaking throughout exposure reduces efficiency.
4. Fill the bottle fully and replace the cover.
5. Place it in the sun for at least 6 h. Table 18-9 provides the required exposure times for three meteorological conditions. To reduce the risk of breaking or contamination of the bottles, place them out of reach of children and off the ground. One good place to place the bottles is on corrugated metal roofs, in between the grooves.
6. The water is ready for consumption after the appropriate exposure time.
7. Replace old or scratched bottles.

Table 18-9. Required Exposure Time for Solar Disinfection (SODIS) Treatment of Water

Conditions	Required Exposure Time
Sunny to 50% cloudy	6 h
50% to 100% cloudy	2 full days
Continuous rainfall	SODIS is not suitable
Water temperature at or above 50 °C	1 h

Source: EAWAG 2002.

18.8 Storage

Water storage is a critical issue (Box 18-4). Water that is clean at the source is often contaminated by the time it is consumed because of poor storage practices. Risk factors contributing to higher contamination include containers with wide openings; water being touched by hand, cups, or dippers that can be contaminated by fecal matter; high storage temperatures; increased storage times; high levels of airborne particles (dust storms); and inadequate hand washing (Sobsey 2002).

Box 18-4 How Safe Is Household Storage?

The drinking water guidelines established by the World Health Organization (WHO), state that the water source should not contain any microbiological agents that are pathogenic to humans (WHO 2006). However, these drinking water guidelines are based on water quality at the point of delivery, not through the point of actual consumption (Wright 2004).

Microbiological contamination of drinking water during collection and storage in the home has been examined by several researchers (VanDerslice and Briscoe 1995; Clasen and Bastable 2003). Agard et al. (2002) examined the microbial quality of water sources supplied to the San Fernando community in southern Trinidad and found that out of the 104 drinking water samples obtained from households, 80.8% tested positive for total coliforms, 53.8% tested positive for thermotolerant coliforms, and 67.3% tested positive for *E. coli*. Out of the 81 water samples collected from the Water and Sewerage Authority distribution point, 46.9% tested positive for total coliforms, 16% tested positive for thermotolerant coliforms, and 33.3% tested positive for *E. coli*. As the level of residual chlorine decreased, there was a statistically significant increase in the prevalence of total coliforms in water from 0.0% in treated reservoir to 80.0% in household drinking water. Agard et al. concluded that the level of household water contamination presented a public health concern to residents.

Brick and Primrose (2004) examined the effects of household storage on water quality in a southern town in India. The study showed that two-thirds of the water sources became increasingly contaminated within nine days of current household storage practices, in spite of receiving safe drinking water from municipal plants. However, the use of brass storage containers significantly decreased contamination of water. Trevett et al. (2004) evaluated the drinking water quality in three rural Honduran communities that used either a protected hand-dug well or bore hole supply. Water quality was examined in 43 households with observations made of household collection and storage practices over a two-year period. There was frequent and substantial water quality deterioration between the points of supply and consumption. Additionally, it was concluded that none of the storage factors examined made any significant difference to the stored water quality and that the contamination could have occurred at several points.

Based on what is reported in the literature, it is thus necessary to take every possible precaution to prevent contamination of water during collection, transport, and household storage.

Box 18-5 How Safe Are Plastic Containers and Tubing?

When designing a water distribution, treatment, or storage system, engineers often are faced with the need to weigh the need for biological treatment of pathogens against potential health outcomes from chemical exposure. For example, some plastic bottles contain the chemical bisphenol A (BPA). BPA is known to be a hormone disrupting chemical in animal studies and has been associated with reproductive abnormalities, precancerous changes in the breast and prostate, and obesity and insulin resistance (NRDC 2008). In the United States, where plastics have been used for decades for storing consumable liquids, more than 93% of the population has some form of BPA in their bodies (CDC 2008).

The Natural Resources Defense Council (NRDC 2008) has recommended that plastics numbered as 1 (PETE), 2 (HDPE), 4 (LDPE), and 5 (PP) are safe and that plastics numbered 7 (other, usually polycarbonate), 3 (PVC or V), and 6 (polystyrene) should be avoided. The NRDC (2008) also recommends that infants in particular should not be given drinks from polycarbonate bottles or cups.

Water that is stored in the home should always be covered. Ideally, the storage container should also have a spout through which water can exit. Otherwise, a dipper can contaminate the water every time it is used. If a spout is not possible, the dipper should be hung from a hook in a clean place (not set on a surface) and it should have a handle, so that no hands (or surfaces that come in contact with hands) ever enter the water (Box 18-5).

Optimal storage containers (Fig. 18-14) have the following characteristics:

- 10–25-L capacity,
- one or more handles,

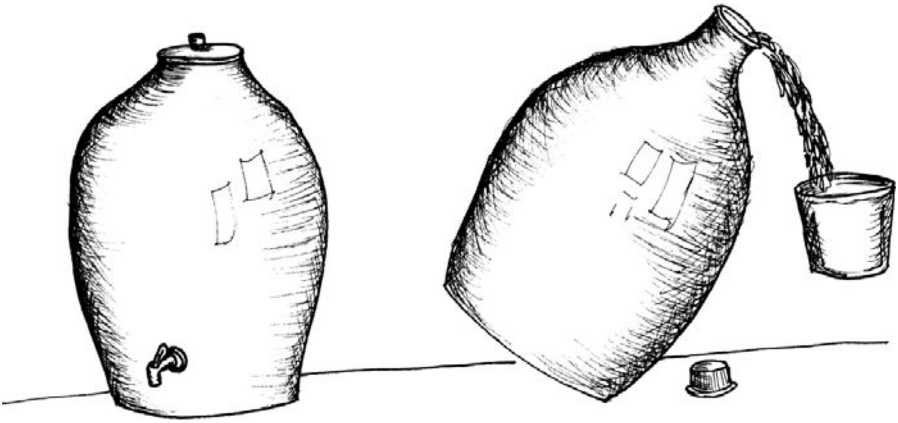

Figure 18-14. Examples of Good Water Storage.

Note: The left container has a lid, narrow neck to prevent dipping cups into it, and a spigot for drawing water. Although the right container does not have a spigot, it is easily poured, and the narrow neck prevents contamination by cups used to draw water. The containers would be easier to use if they had handles.

- flat bottoms,
- construction of light-weight, oxidation-resistant plastic (e.g., polyethylene or polypropylene),
- a 6–9-cm screw cap (big enough to allow cleaning but small enough that it discourages using hands or dippers to access the water),
- a durable and easily closed spigot or spout to dispense water, and
- pictorial and written instructions permanently attached to the container (Sobsey 2002).

Storage containers also need to be compatible with the water treatment methods being used by the household.

18.9 Measuring Turbidity with a Turbidity Tube

Turbidity is easily measured in the field by a turbidity tube, which is simple to construct (Myre and Shaw 2006). The procedure for measuring turbidity is depicted in Fig. 18-15. Pour water into the tube until the black-and-white quartered pattern located at the bottom of the tube can no longer be seen. The height of the column of water when the pattern disappears corresponds to the turbidity of the water, as shown in Table 18-10. A shadow should be cast on the tube while measurements are being taken, for example by standing between the sun and the tube.

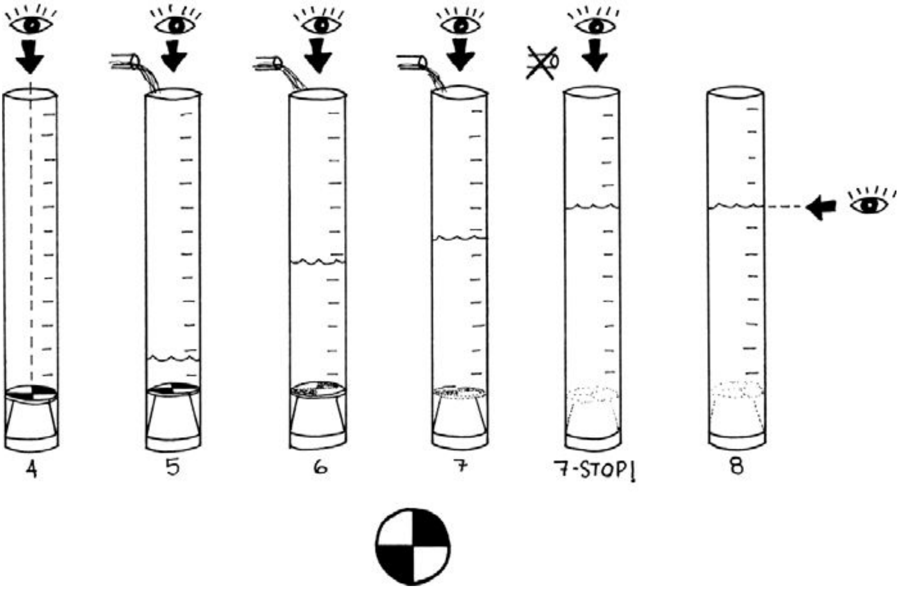

Figure 18-15. Measuring Turbidity with a Turbidity Tube.

Note: If a water sample is more turbid, the quartered disk located at the bottom will disappear with a smaller volume of water added to the tube.

Table 18-10. Conversion of Length to Turbidity When Using a Turbidity Tube

Centimeters	NTU
6.7	240
7.3	200
8.9	150
11.5	100
17.9	50
20.4	40
25.5	30
33.1	21
35.6	19
38.2	17
40.7	15
43.3	14
45.8	13
48.3	12
50.9	11
53.4	10
85.4	5

Source: UW Extension 2003.

18.10 Arsenic

18.10.1 Arsenic Occurrence and Chemistry

The occurrence of arsenic in groundwater in many parts of the world is significant enough to require removal. Exposure to high levels of arsenic rarely causes acute poisoning, but long-term exposure can result in skin diseases that can eventually lead to urinary bladder and lung cancer, damage to internal organs, gangrene in the legs, and hypertension. When developing a source of groundwater in regions where arsenic is known to exist, it is important to know whether treatment is necessary.

Arsenic poisoning may be difficult to diagnose in cases where internal organs are affected first. However, visible symptoms exist, such as darkening of the skin, hardening of the palms of the hands and the soles of the feet, or skin depigmentation. Naturally occurring arsenic in drinking water supplies has been found throughout the world (Table 18-11), but the problem is most serious in Bangladesh and West Bengal, India, where millions of wells were installed in the 1970s and 1980s to provide what was thought to be safe drinking water.

Arsenic occurs in both particulate and soluble forms. Particulate arsenic can be removed by a 0.45-µm filter (Petrusevski et al. 2007). Soluble arsenic is more difficult to remove and requires an understanding of the chemistry of soluble arsenic to plan treatment methods. Treatment of arsenic in drinking water is the subject of current research and technology development (Amy et al. 2005; SenGupta 2005; Petrusevski et al. 2007).

Table 18-11. Countries Where Arsenic Has Been Reported in Groundwater

Continent	Countries
Asia	Bangladesh, Cambodia, China (including Taiwan and Inner Mongolia), India, Iran, Japan, Myanmar, Nepal, Pakistan, Thailand, Vietnam
Americas	Argentina, Chile, Dominica, El Salvador, Honduras, Mexico, Nicaragua, Peru, United States
Europe	Austria, Croatia, Finland, France, Germany, Greece, Hungary, Italy, Romania, Russia, Serbia, United Kingdom
Africa	Ghana, South Africa, Zimbabwe
Pacific	Australia, New Zealand

Source: Petrusevski et al. 2007.

In natural waters, soluble arsenic occurs primarily in the oxidized pentavalent form [As(V)] (which occurs mostly in surface water) and the more toxic trivalent form [As(III)] (most often found in groundwater). Table 18-12 shows the many forms of soluble arsenic found in groundwater and surface water.

Table 18-13 lists treatment processes used to remove arsenic from water. Conventional treatment technologies involve processes that are heavily dependent on surface charge, and therefore speciation. As Table 18-12 shows, As(V) occurs primarily as an anion in natural surface waters, and therefore, removal of As(V) is easier than removal of As(III). Most arsenic removal technologies involve chemically oxidizing As(III) to As(V), followed by conventional adsorption and coprecipitation.

Table 18-12. The Forms of Soluble Arsenic Found in Groundwater and Surface Water

Valency	Speciation	Form	Primary Occurrence	pH at Which Ionic Forms Dominate
Arsenite [As(III)]	$H_4AsO_3^+$ H_3AsO_3 $H_2AsO_3^-$ $HAsO_3^{2-}$ AsO_3^{3-}	Reduced	Groundwater, assuming anaerobic conditions[a]	pH > 9
Arsenate [As(V)]	H_3AsO_4 $H_2AsO_4^-$ $HAsO_4^{2-}$ AsO_4^{3-}	Oxidized	Surface water	pH > 3

Note: Treatment technologies require that ionic species dominate. Because As(V) is ionic at natural pH, it is easier to remove than As(III).

[a] The generalization that As(III) is most often dominant in groundwater is less universal than the rule that As(V) dominates surface water. As(V) has been found in groundwater.

Source: Petrusevski et al. 2007.

Table 18-13. Proven Processes Used to Remove Arsenic That Can Be Feasible for Developing Communities

Process	Technologies
Precipitation	Coagulation and flocculation Coagulation-assisted microfiltration Enhanced coagulation Lime softening Enhanced lime softening
Adsorption	Activated alumina Activated carbon Iron and manganese oxide based or coated filter media
Ion exchange	Anion exchange
Membrane filtration	Nanofiltration Reverse osmosis Electrodialysis

Note: Other technologies exist but would either be too costly or are still in the development stage.

Source: Petrusevski et al. 2007.

18.10.2 Arsenic Treatment

In the absence of treatment, arsenic-contaminated wells can simply be painted with a distinguishing color. Arsenic removal in developing communities uses conventional precipitation and adsorption processes. A typical precipitation process to remove arsenic in groundwater would involve aeration, followed by coagulation and flocculation with aluminum or iron salts, followed by sedimentation and rapid sand filtration. If As(III) is known to be a significant portion of the arsenic in the water, a chemical preoxidation through chlorination or ozonation may be required. However, this process increases treatment costs and may result in oxidation by-products (Petrusevski et al. 2007). After treatment, the liquid waste should be treated as toxic. Adsorption processes have in the past used activated alumina; more recently, iron-based adsorbents are being used. A typical iron-based adsorption process involves a series of adsorptive filters and has no requirement for chemical addition (Petrusevski et al. 2007). Iron oxide coated sand can also be used as an arsenic adsorbent.

Table 18-14 lists some common systems that have been used with limited success at the household level. Figure 18-16 shows a treatment unit that uses granular activated alumina. The exhausted activated alumina is disposed of below the ground in a concrete-lined vault.

18.11 Fluoride

Fluoride in drinking water can have negative or positive effects on human health, depending on concentration. Industrialized drinking water treatment often includes addition of fluoride because concentrations of approximately 1 mg/L are associated with reduced

Table 18-14. Common Processes for Point-of-Use Arsenic Removal and Examples of Systems That Use Them

Process	System	WaterAid (2001a, b) Test Result
Passive sedimentation	Passive sedimentation	Failed
Passive sedimentation and adsorption	Ardasha filter	Failed
Adsorptive filtration	Alcan enhanced activated alumina	Passed
	BUET activated alumina filter	Passed
	Apyron arsenic treatment unit	Not tested
	Read-F arsenic removal unit	Not tested
	Wellhead arsenic removal systems developed by Dr. Arup K. SenGupta and others at Lehigh University	Not tested by WaterAid (2001), but proven successful by Sarkar et al. (2005)
	UNESCO-IHE family filter (iron oxide coated sand)	Not tested by WaterAid (2001), but proven successful by Khan (2004)
Coagulation	DPHE-Danida bucket treatment unit technology system	Passed under certain conditions
	Garnet filter	Passed under certain conditions
	Stevens Institute	Passed
Ion exchange	Tetrahedron	Passed
Coagulation and adsorption	Sono 3-Kalshi filter	Passed

Note: Nine of these systems were tested by WaterAid for successful removal to below the Bangladeshi standard of 50 μg/L.

Sources: Khan (2004); Sarkar et al. (2005); and Petrusevski et al. (2007) with data from WaterAid (2001a,b).

incidence of dental cavities. Excessive levels of fluoride are associated with a number of negative health effects, including dental fluorosis (staining of teeth and erosion of enamel) and skeletal fluorosis (resulting in osteosclerosis, ligamentous and tendinous calcification, and extreme bone deformity).

Fluoride exists in natural waters primarily as the fluoride ion (F^-) or as a complex with aluminum, beryllium, or ferric iron (Crittenden et al. 2005). Because fluoride ions have the same charge and almost the same radius as hydroxide ions, they form mineral complexes with many cations (Fawell et al. 2006). Fluoride is therefore found abundantly in the Earth's crust, occurring in a variety of minerals. When calcium is present, fluorite is common (CaF_2), which has low solubility. Therefore, higher concentrations of fluoride in solution occur in calcium-poor aquifers where fluoride-bearing minerals are common.

Water is not the only exposure pathway for humans to fluoride. Fluoride can also be found in air, dental products, and foods and beverages other than water. Therefore, if dental or skeletal fluorosis exists, it may not necessarily mean that fluoride removal from