Pergamon

PII: S0038-092X(98)00036-X

Solar Energy Vol. 64, Nos 1–3, pp. 87–97, 1998
Published by Elsevier Science Ltd
Printed in Great Britain
0038-092X/98 $—see front matter

WATER DISINFECTION FOR DEVELOPING COUNTRIES AND POTENTIAL FOR SOLAR THERMAL PASTEURIZATION

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Received 25 September 1997; revised version accepted 25 February 1998

Communicated by JAMES BOLTON

Abstract—Water-borne disease in developing countries leads to millions of deaths and billions of illnesses annually. Water disinfection is one of several interventions that can improve public health, especially if part of a broad program that considers all disease transmission routes and sustainably involves the community. Considering water volumes $\lesssim 30$ m^3/day, appropriate disinfection methods include chlorination, slow sand filtration, ultraviolet (UV) radiation and pasteurization. Pretreatment with a coarse roughing filtration is generally used with the first three of these technologies to reduce turbidity and maintain high effectiveness. Cysts and worm eggs are resistant to chlorination and UV but can be filtered relatively easily. Chlorination is widely used and inexpensive but requires a continual supply of chemicals. Slow sand filtration is lowest in cost but requires high investment in labor. Household filtration using indigenous devices requires little capital investment but is relatively ineffective and difficult to properly maintain. Batch treatment with solar UV is very easy to implement but effectiveness in practice is uncertain since temperatures above 50°C should be attained. UV lamp devices are inexpensive and easy to use but require power and access to maintenance infrastructure. Boiling of water requires no initial expense but fuel and labor costs are very high. Solar pasteurization devices (batch and flow-through) are effective and relatively maintenance-free, but existing products yield high treatment cost. Flow-through systems with selective flat plate collectors become cost-competitive with UV technology at costs of about \$380/m^2 and \$80/m^2 for home-scale and village-scale use, respectively. These cost goals might be attained with polymer thin film designs if durability issues are adequately resolved. Published by Elsevier Science Ltd.

1. INTRODUCTION

1.1. *Problem characterization*

The need for water disinfection in the developing world is indisputable. Water-borne diseases cause about five million deaths per year, at least half of which are children (UNICEF, 1995). The average child experiences more than two episodes of diarrhoea each year; frequent episodes of diarrhoea leave victims weakened and malnourished, resulting in greater susceptibility to other diseases and, for adults, loss of productivity (Snyder and Merson, 1982). Roughly 50% of hospitalizations are from water-borne disease (Alward *et al.*, 1994). The major pathogens of concern, their sizes, and associated diseases are listed in Table 1. The fecal–oral cycle is the basis of transmission of most of these pathogens.

The source of the water largely determines water characteristics. Water sources, in order of decreasing quality, include springs, boreholes, sealed wells, hand-dug wells, streams, rivers, and lakes. Springs and boreholes tap groundwater sources that have been filtered through layers of soil and rock and are isolated from the surface. These sources may contain unpleasant color, odor, or minerals, but generally are free from pathogen contamination and should not require disinfection. Sealed wells are shallow wells that have been sealed with cement around a pump to prevent contamination. However, contamination is possible, and sealed wells are often treated with chlorine. Wells become contaminated from improper usage and from contaminated water entering the well from above, particularly during flooding. Hand-dug wells are typically contaminated. Finally, streams, rivers, and lakes usually contain pathogens and require disinfection.

Table 1. Water-borne pathogens

Pathogen class	Size	Diseases
Bacteria	0.5–2 μm	Diarrhoea, cholera, enteric and typhoid fever, dysentry
Viruses	20–80 nm	Heptatis, polio, diarrhoea, meningitis, lung diseases
Protozoa	4–20 μm (cysts)	Giardiasis, amoebic dysentery, diarrhoea
Helminths (worms)	0.03–2 mm (eggs)	Round worm, guinea worm, schistosomiasis

Water disinfection significantly improves public health, but in and of itself is not a panacea for water-borne diseases. There are other means of transmission. Any contact between the feces of a contaminated person and what another person ingests (water, food, utensils, dirt) may result in spread of disease. Education of the users is crucial so that they do not dip unwashed hands or utensils into storage vessels, especially when no residual disinfectant is present. Other intervention measures are also needed, including increased supply and sanitation. Increased water supply leads to better hygiene. Widespread effective waste sanitation breaks the fecal–oral cycle at the source and reduces the pathogen intake. Generally, the balance between intervention measures (disinfection, hygiene education, additional water supply, and sanitation) should be carefully weighed and optimized (Feachem *et al.*, 1977). Thus, it is important to be realistic about the benefits that will actually be obtained from water disinfection. Observed morbidity reductions for single and combined measures are shown in Table 2. Apparent inconsistencies in Table 2 reflect the high variability in the limited data sets available.

Table 2. Observed reductions in diarrhoeal disease morbidity ([Esrey et al., 1991])

Improvement	Mean reduction in morbidity (%)
Hygiene	33
Water quantity	27
Sanitation	22
Water quality	17
Water quantity and sanitation	20
Water quality and quantity	16

1.2. Water disinfection: general issues

Just listing some of the relevant technical and sociological variables related to water disinfection helps in understanding why the problem has remained so pervasive for so long. Relevant variables include: *water pathogens*—bacteria and viruses are commonly found in nearly all surface water and most groundwater, but protozoa and worms are less widespread, require different treatment, and often have similar symptoms; *water turbidity*—clean well water to turbid river water (affects filtration design in multi-stage treatment); *local population density*—urban, village, and widely dispersed single family (impacts disinfection system capacity); *water use*—from several to several hundred liters per day per person (depends heavily on water supply method); *availability of electricity*—reliable, questionable, or none (impacts effectiveness and/or cost of systems that require electricity); *existing water disinfection*—acceptable, questionable (some urban dwellers boil "treated" water), or none; *local labor cost*—low labor costs make labor-intensive technologies more attractive; *community structure*—complex cultural issues can be barriers to functioning water treatment management structures; *infrastructure issues*—varying access to supplies, training for operation, maintenance and repair, management support, and method of billing; *sanitation practices*—affects exposure locally and "downstream"; *hygiene practices*—dependent on water supply and culture (other transmission paths); *income*—affects ability to pay for (and thus sustain) water disinfection; and *awareness of disease* (the fecal–oral cycle)—affects motivation to invest in and maintain water disinfection.

Many authors emphasize two points related to these many complex variables. First, willingness to invest in water disinfection is crucial: without community involvement and development of infrastructure (such as means of billing to sustainably fund maintenance needs), any water disinfection facility becomes non-functional and is useless (World Bank, 1993). Second, access to supplies, spare parts, and training (all obviously important for facility maintenance) heavily impacts technology choice. A useful anecdote is the failure of well-sealing programs when an infrastructure to keep the hand pumps operational was not also implemented (WASH, 1993).

Water turbidity also impacts the choice of water disinfection methods. Turbidity is a measure of the amount of solid particles suspended in water, commonly determined by light scattering and measured in "nephelometric turbidity units" (NTU). The turbidity of well water is quite low (<10 NTU), while the turbidity of dirty river and lake water varies widely (10–2000 NTU). Turbidity is caused by suspended material such as small particles (e.g. bits of organic matter), fecal matter, or colloids (micron-sized clay particles). These particles can reflect or absorb ultraviolet (UV) radiation, decreasing the effectiveness of UV disinfection. In addition, these particles, particularly colloids, serve as shelters for microorganisms, shielding them from UV and chemical disinfectants. Finally, high turbidity levels cause filters to become clogged rapidly, thereby increasing the maintenance needs of filters. Each technology (except for pasteurization devices) specifies maximum turbidity for inlet water.

The effectiveness of disinfection systems also depends on the types of pathogens present. Protozoa form cysts when under stress. Cysts have a tough, protective encapsulation that is resistant to UV and chemical disinfection. Worms and worm eggs are also resistant to UV and chemical disinfection. Viruses are difficult to remove by filtration because of their small size (slow sand filters are an exception). Some bacteria contain enzymes that repair their DNA after damage by UV radiation, in presence of light (photoreactivation) or without light (Wegelin *et al.*, 1994; Ellis, 1991). These mechanisms allow bacteria to gradually "regenerate" themselves after UV exposure. Wegelin *et al.* (1994) show regeneration data with significant repair after as little as 24 h. Therefore, water treated by UV should be used within a reasonable time after disinfection, with one recommendation being within 36 h (Gadgil and Shown, 1997).

An important concern with any water disinfection that does not leave residual disinfectant in the water is the potential for recontamination after disinfection and before ingestion. Recontamination often occurs from poor hygiene and storage container handling. Leaky distribution pipes can be contaminated during periods of heavy rains. Of the treatments discussed here, only chlorination leaves a residual in water that can disinfect subsequent contamination. Disinfection of water just before it is used removes some of the potential for recontamination.

Classes of water disinfection methods include chlorination, filtration, UV, and pasteurization. This paper discusses and compares specific methods appropriate for smaller volume applications ($\lesssim 30$ m^3/day) in developing countries. Technologies are selected on the basis of low cost (actual or potential) and/or historical use by various water development programs.

2. APPROPRIATE WATER DISINFECTION ALTERNATIVES

Technologies are evaluated on the basis of normalized costs and appropriateness. Appropriateness indicators include technology effectiveness (including residual disinfection), and technology "convenience" (relating to need for supplies, and high and low cost labor). The normalized cost indices are the cost of treated water (C_{water}) and the capacity cost (C_{cap}), based on standard life-cycle costs (LCC), including first cost and all operation and maintenance costs. These costs are computed using the present worth factor (PWF) and diurnal volumetric capacity (V_{d}):

$$\text{LCC} = C_0 + C_{\text{OM}} \times \text{PWF}(N_{\text{years}}, d, i)$$

$$C_{\text{water}} = \text{LCC}/[\text{PWF}(N_{\text{years}}, d, i) \times V_{\text{d}} \times 365]$$

$$C_{\text{cap}} = C_0 / V_{\text{d}}$$

The first cost C_0 includes hardware cost and installation labor; if hardware is imported, the FOB ("freight on board") cost is multiplied by 1.3 to account for international business costs. Grid electricity is assumed as 10 ¢/kWh (if applicable). C_{OM} is the cost for annual fuel, materials, repair and operating labor. d is the discount rate (0.2 assumed), i is the inflation rate (0.1 assumed). N_{years} is the system lifetime in years. The technology lifetime is taken as 20 yr, except for solar systems (15 yr for metal systems, 10 yr for polymer systems), home ceramic filters (2 yr) and plastic bottles (1 yr).

Detailed assumptions for each technology are given in Burch and Thomas (1998a) and results are summarized in Table 3. It is emphasized that these costs (especially with chlorination and filtration) have large ranges and tend to show considerable variation between references. The costs reported here are at the low end of costs purported to be applicable to developing countries.

2.1. *Chlorination*

Chlorine is the most common form of water disinfection used worldwide. Small-scale dosing plants and household batch methods are considered here. Chlorine is relatively low-cost [costs assumed are 1 ¢/g for batch use (Water for People, 1997), and 0.5 ¢/g for dosing plants]. A primary advantage of chlorine is that the chlorine residual disinfects recontaminated water. The chlorine residual depends on several factors besides the added dose, including "biological oxidation demand" and pH. The primary disadvantage of chlorine is that a constant supply is needed, because liquid bleach degrades over time (half-life on the order of two months, depending upon whether the container is sealed when not in use). Bleaching powder has a longer half-life, on the order of one year, depending on whether it is kept dry (Harris, 1992). Cholera outbreaks have been reported in India when

Table 3. Appropriate disinfection technologies: cost and appropriateness summary

Variables/technologies	Production	First cost	Capacity cost	Life cycle cost	Effectiveness[†]			Convenience[‡]		
Units or subcategories	l/day	$	$/m^3/day	¢/m^3	Res[¶]	B/v[§]	P/w[#]	Sup[††]	Hi[‡‡]	Lo[¶¶]
Chlorine dose + roughing filter	24000	2400	100	6	***	***	**		*	*
Slow sand + roughing filter	24000	2160	90	3		**	***	***	***	*
UV + PV (8 h) + filter	7200	2366	329	14		***	**	*	*	**
Chlorine batch	200	0	0	9	**	***	*		***	**
Household filter	60	20	333	85		*	**	***	***	**
Home UV + PV[§§] + filter	500	381	761	63		***	**	*	*	*
Sol-UV[##]/batch bottles	14	1	43	133		*		***	***	**
Water boiling (purchased fuel)	20	0	0	2083		***	***		***	**
Batch solar: existing 1 m^2	23	78	3425	235		***	***	***	**	***
Flow-thru solar: existing 3 m^2	570	2145	3764	144		***	***	***	***	**
Solar: potential polymer 1 m^2	304	84	276	19		***	***	***	***	**

[†] Effectiveness scales: high = ***, medium = **, low = *, none = blank (more stars = more effective).

[‡] Convenience scales: no need = ***, low = **, medium = *, high = blank (more stars = more convenient).

[¶] Res = residual disinfection ability.

[§] B/v = effectiveness against bacteria and viruses.

[#] P/w = effectiveness against protozoa and worms.

[††] Sup = need for supplies.

[‡‡] Hi = need for high-skilled labor.

[¶¶] Lo = need for low-skilled labor.

[§§] PV = photovoltaics.

[##] Sol-UV = solar UV.

impassable roads blocked the chlorine supply during heavy storms (Gadgil and Shown, 1997).

A proper chlorine dose is complex to determine. The required chlorine base is specified in parts per million (ppm) residual (mg/l) times exposure minutes (mg min/l). The dose depends on many factors. Higher doses are needed for cysts and eggs (2–100 mg/min/l) than for viruses and bacteria (0.04–3 mg/min/l) (Feachem *et al.*, 1983; World Health Organization, 1996). The dose increases roughly eight-fold for an increase in turbidity from 1 to 10 NTU, increases roughly ten-fold for an increase in pH from 6 to 10, and decreases roughly ten-fold for a 20°C increase in water temperature. Too high a chlorine dose makes taste objectionable. Automated dosing plants using chlorine gas, chlorine dioxide, and chloramines are suitable only for larger towns with trained operators and accessible repair infrastructure. Bleaching powder is generally used in developing countries because it is easier to transport and handle safely. It may be applied as a liquid solution in a drip-chlorination plant. Chlorine dosing plants are costed at \$100/m^3/day (Schulz and Okun, 1984), and an average chlorine dose of 1 ppm is assumed. For small-scale batch use, a 1% liquid solution may be made from bleaching powder at a central health post and distributed to individual households, which then add a given amount of the solution to every bucket of water (Water for People, 1997).

2.2. *Filtration*

2.2.1. Roughing filter. To operate correctly, chlorine, slow sand filtration, and UV disinfection systems require pretreatment of water with high turbidity levels. For small-scale devices, a "roughing filter" is used, which is a multi-stage filter with relatively coarse filtration media. There are several possible configurations of roughing filters for village-scale use, including downward flow, upward flow, and horizontal flow. Figure 1 shows a horizontal flow roughing filter. The filter consists of 5 to 9 m total thickness of gravel in three layers: coarse gravel, fine gravel, and coarse sand. The grain size and flow rates are much larger than those used in slow sand filters. The filter can remove up to 900 NTU of turbidity, and also removes about 90% of bacteria, protozoa, and worms (Wegelin *et al.*, 1991). Operation is fairly straightforward, requiring untrained laborers for most tasks. Supplies of chemicals or spare parts are not required. Head loss is normally less than 30 cm. Maintenance consists of monthly cleaning by rapidly flowing water through the filter. Occasionally, manual removal, washing, and replacement of filter media is required (Wegelin *et al.*, 1991). A first cost for the roughing filter is taken as \$40/m^3/day (Water for People, 1997).

2.2.2. Slow sand filter. Slow sand filtration (SSF) is a very popular method of water disinfection among nongovernmental organizations (NGOs) involved with water, as well as among small towns in the developed world (EPA, 1991). Figure 2 shows a schematic of a low sand filter. Designs are available that mostly eliminate the need for costly hardware (such as valves and pumps). SSF involves filtering water through about 100 cm of fine sand at a rate slow enough for a biological film (the schmutzdecke) to develop on top of the sand. At the slowest rates, water flows through the SSF at about 2 m^3/day/m^2 surface area. This rate determines the SSF surface area. The top film serves as a biological filter that effectively removes over 99% of all pathogens (Schulz and Okun, 1984). SSF operation is fairly straightforward, requiring untrained laborers for most tasks. Supplies of chemicals or spare parts are not required, which is a primary advantage of SSF. The only energy requirement is for pumping to compensate for 6 to 120 cm of head loss (head loss increases gradually after scraping as the biological layer builds). The majority of SSF are designed for gravity-feed operation (Schulz and Okun, 1984). Maintenance involves periodic raking of the biological film (every few weeks, depending on water turbidity), scraping off the top layer of sand every few rakings, and replacement of a few inches of sand every few scrapings. A disadvantage of SSF is that the biological filter requires a period of several days to "ripen" after every scraping. During the ripening period, the filter does not effectively remove bacteria. Therefore, multiple filters are generally used in parallel. To reduce the frequency of scrapings, it is recommended that a roughing filter be used for pretreatment of waters of turbidity greater than about 20 NTU (Water for People, 1997). The SSF first cost is taken as \$50/m^3/day (Water for People, 1997).

2.2.3. Household filtration. Household filters common in the western world require periodic media replacement and are far too expensive for use in developing countries. Many indigenous designs are used, ranging from simple pots

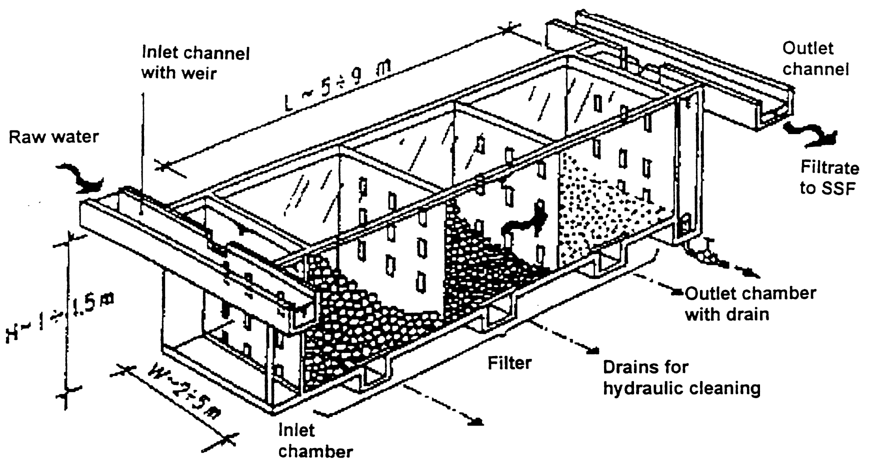

Fig. 1. A schematic of a horizontal roughing filter (from [Wegelin et al., 1991]). Three stages are shown, water traveling left to right through coarse gravel, finer gravel, and coarse sand. Viruses and bacteria will pass through the roughing filter.

filled with sand through which water is poured to complex designs incorporating upward flow, several ceramic layers, and multiple sand and charcoal layers. One design is shown in Fig. 3. A primary advantage of home filters is that they can be produced by local craftspeople. These filters form part of the traditional way of life in many parts of the world. Testing of some indigenous filters has shown that most can remove 90–99.99% of bacteria and the finer filters can also remove 90% of viruses (Gupta and Chaudhuri, 1992). Note that an infective dose for virus is a small number, and 90% filtration may be of little value. Filter effectiveness is determined by the size of the filter pores, absorptive forces within the filter media, and the presence of cracks in the filter. Poorer quality filters remove only 90% of bacteria, which can mean that millions of bacteria may be left behind in very poor quality water. Ceramic filters produced by hand may vary widely in quality or contain cracks. Finally, filter quality can deteriorate over time, unknown to the user. Filters must be regularly cleaned, either by boiling or backwashing, and periodically replaced. For cost analysis, filter cost is assumed at $20, production at 60 l/day, and replacement at two years.

2.3. *UV radiation*

UV water disinfection (including technical data, advantages, and disadvantages) is discussed by Schenck (1981) and Ellis (1991). UV light from mercury discharge is produced near 250 nm, in the middle of the "germicidal band" from 200 nm to 280 nm. Germicidal UV radiation disables the DNA involved in reproduction of bacteria and viruses, rendering these pathogens harmless upon ingestion. Lamp-driven UV is a comparatively inexpensive and easy to use technology. It has a relatively low power demand. Systems can be designed for household

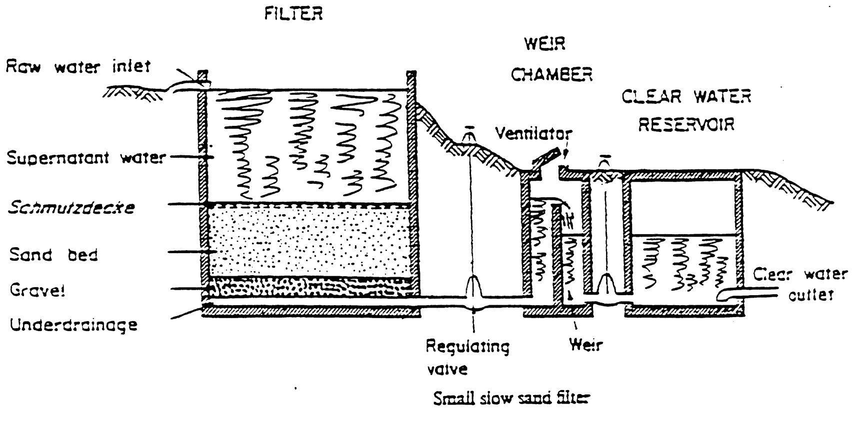

Fig. 2. A schematic slow sand filter (from [Feachem et al., 1977]). The water is filtered through fine sand, building up a biological layer atop the sand (the "schmutzdecke"). The sand is atop gravel and under drainage. Gravity feed is shown.

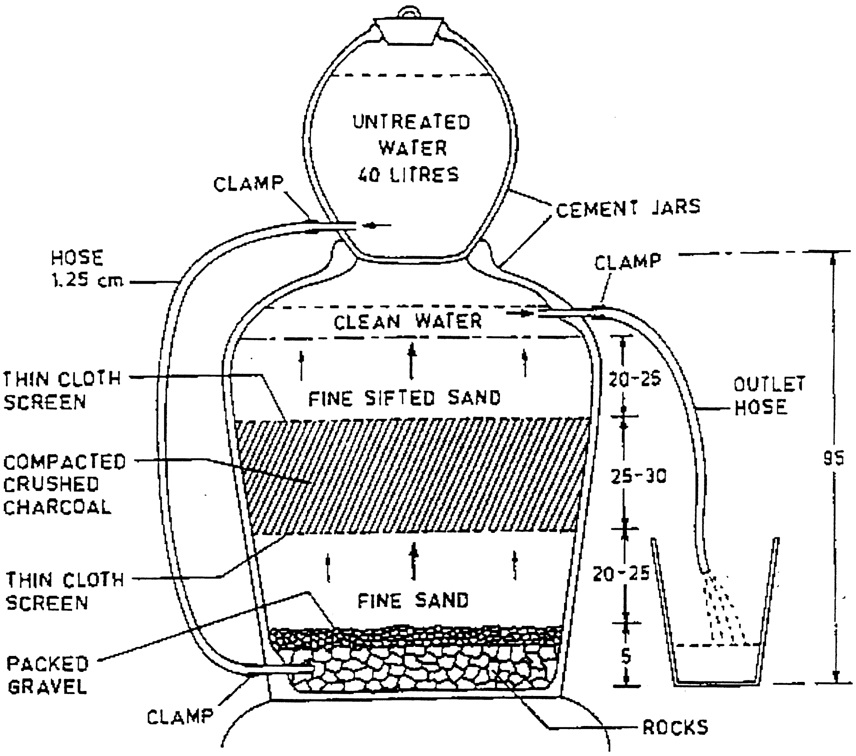

Fig. 3. A schematic home filter (from [Gupta and Chaudhuri, 1992]). An upflow unit is shown, with head provided by an upper jar that feeds the lower filtration jar. The unit incorporates two sand layers separated from a charcoal layer by thin cloth screens, and a gravel layer and a rock layer at the inlet for rough filtering.

or village-scale use. Photovoltaics (PV) or other renewable power sources are needed for off-grid locations. Filtering for cysts/worms and lowering of turbidity to acceptable levels ($\lesssim$ 20 NTU) will frequently be needed, and is assumed here. The roughing filter capital cost is assumed to be \$40/m^3/day. A recent village-scale unit discussed in Gadgil and Shown (1997) is projected to cost about US\$525 FOB, and produces about 21 m^3 of water per day when running continuously at maximum throughput of 15 l/min. The 36 W UV bulb must be replaced at about 8000 h of operation, and the ballast lifetime is about 24,000 h. For off-grid locations of interest here, PV is assumed added. The PV system costs (including batteries and controller) are taken as US\$10/W FOB, with maintenance costs of battery replacement plus 1% per year of system first cost. System efficiency is assumed to be 0.6. At an average daily irradiation of 5 kWh/m^2, the cost of PV electricity is about \$1/kWh. With these assumptions, UV treatment cost with (without) PV is 14 ¢/m^3 (4 ¢/m^3).

A home-scale UV + PV + filter unit is appropriate. An 8 W bulb/chamber combination is available at very low cost (~US\$50/unit FOB). This unit is intended to run continuously. Potentially, such a unit could be combined with an appropriate filtration unit (not the multi-stage filters designed for developed world markets), though our study did not locate such units commercially. An appropriate home filter is estimated at \$80/m^3/day, which is twice the cost of large-scale pretreatment filtering. When combined with PV, such units appear a cost-effective and convenient choice for single family markets if access to technical infrastructure is not an issue.

Because of basic black body effects and atmospheric absorption, natural UV from the sun is relatively weak and predominantly at relatively long wavelengths ($\gtrsim$300 nm). It is much less effective per unit energy than germicidal UV in disabling pathogens, making its use challenging at best. However, combining natural UV radiation and heat may be practical because of synergistic heat/UV affects (Wegelin *et al.*, 1994). Based on this mechanism, small-scale batch techniques using appropriately blackened plastic bottles and bags are being field tested (Wegelin and Sommer, 1996). It is not clear that sufficiently high temperatures will be attained under cold and/or windy conditions. However, being extremely simple, this approach appears useful if no other means of disinfection is available. Cost analysis was done for plastic bottles assumed to cost $0.01 and to last one year.

2.4. Pasteurization

Thermal disinfection of liquids (water, milk, etc.) is termed "pasteurization" after L. Pasteur who first articulated the fundamental germ basis of infectious diseases. Pasteurization by boiling of water has long been recognized as a safe way of treating water contaminated with enteric pathogens. In fact, pasteurization can take place at much lower temperatures than boiling, depending on the time the water is held at the pasteurization temperature. Process requirements for major pathogens are given in Feachem *et al.* (1983) and are summarized in Fig. 4. Pasteurization time decreases exponentially with increasing temperature. Above 50°C, time decreases at roughly a factor of 10 for every 10°C increase in pasteurization temperature. Viruses appear the hardest to kill and essentially set the boundary for acceptable time–temperature processes (Feachem *et al.*, 1983). A typical process is 75°C for 10 min. The major advantage of pasteurization is that apparently all major pathogens of concern are killed, independent of turbidity, pH, and other parameters influencing alternative methods. Filtering is not required. The major disadvantage of pasteurization is its high cost.

2.4.1. Batch processes. Boiling water on a home scale requires no initial capital and is very effective, but has a very high cost in labor and fuel. Gathered fuel may be free, but causes high environmental damage and consumes inordinate amounts of time. Purchased fuel is assumed for cost analysis here. The cost of boiling water is taken as $0.02/l (Andreatta *et al.*, 1994), consistent with a charcoal cost of $0.018/MJ and a stove efficiency of 25%. One supplier (Hartzell, 1997) manufactures an efficient burner combined with heat exchanger to preheat incoming water that increases the throughput per unit fuel by 5–10 times, depending on the base case. Alternatively, solar heat can be used. Andreatta *et al.* (1994) detail a site-built batch system, which uses polymer thin films and indigenous materials. This is a good example of a potentially inexpensive system, although the durability of the thin films needs further investigation. Manufactured systems include polybutylene tubes in a flat plate configuration costing US$60 FOB (Hartzell, 1997) and an evacuated tube device costing US$95 FOB (Hamasaki, 1997). Both devices have about 20 l capacity and might cycle twice per day under ideal circumstances. Although manufactured batch solar devices are relatively inexpensive and extremely easy to use, the devices do not have large throughput, leading to relatively high treatment cost.

2.4.2. Flow-through solar thermal. Flow-through solar thermal devices are discussed in Andreatta *et al.* (1994). A schematic of a flow-through solar thermal water pasteurization system is shown in Fig. 5. Cold water entering the system passes through the heat exchanger first, where it is preheated by the hot pasteurized water leaving the collector. The throughput of the solar thermal devices of this type depends primarily upon the collector parameters and the effectiveness of the heat exchanger. After an initial transient, the solar collector serves primarily to provide the heat needed because of the "ineffectiveness" of the heat exchanger. A detailed performance analysis can be found in Burch and Thomas (1998b). Throughput is more than 300 l/m^2/(clear day) for flat-plate collectors with selective absorbers. Maintenance needs include rebuilding the control valve at intervals depending on water characteristics. Two systems are reported here: a recently-emergent 3 m^2 system with a shell-in-tube heat exchanger, costing US$1500 FOB and lasting 15 yr; and a potential 1 m^2 system using thin film polymers for collector and heat exchanger, costing $64 and lasting for 10 yr. For cost analysis, throughput must accommodate cloudy conditions. Manufacturer's data is used for the existing system; an average value of 200 l/m^2/day is taken for the potential system.

It is important to note that solar devices with metallic passageways can fail from freeze damage and scale deposition. Freeze damage is usually serious, amounting to ruptured piping, and leads one to restrict the application of solar devices with metal tubes to non-freezing climates. Scale deposition requires periodic descaling, such as with acetic acid. Good tools exist for assessment of the potential severity of the scaling problem, if data on relevant water characteristics are available (Vliet, 1997). Caution should be used in deploying any pasteurization device with metal tubes in hard-water areas.

3. TECHNOLOGY COMPARISONS

An economic comparison of selected technologies is given in Table 3 and Fig. 6. In general,

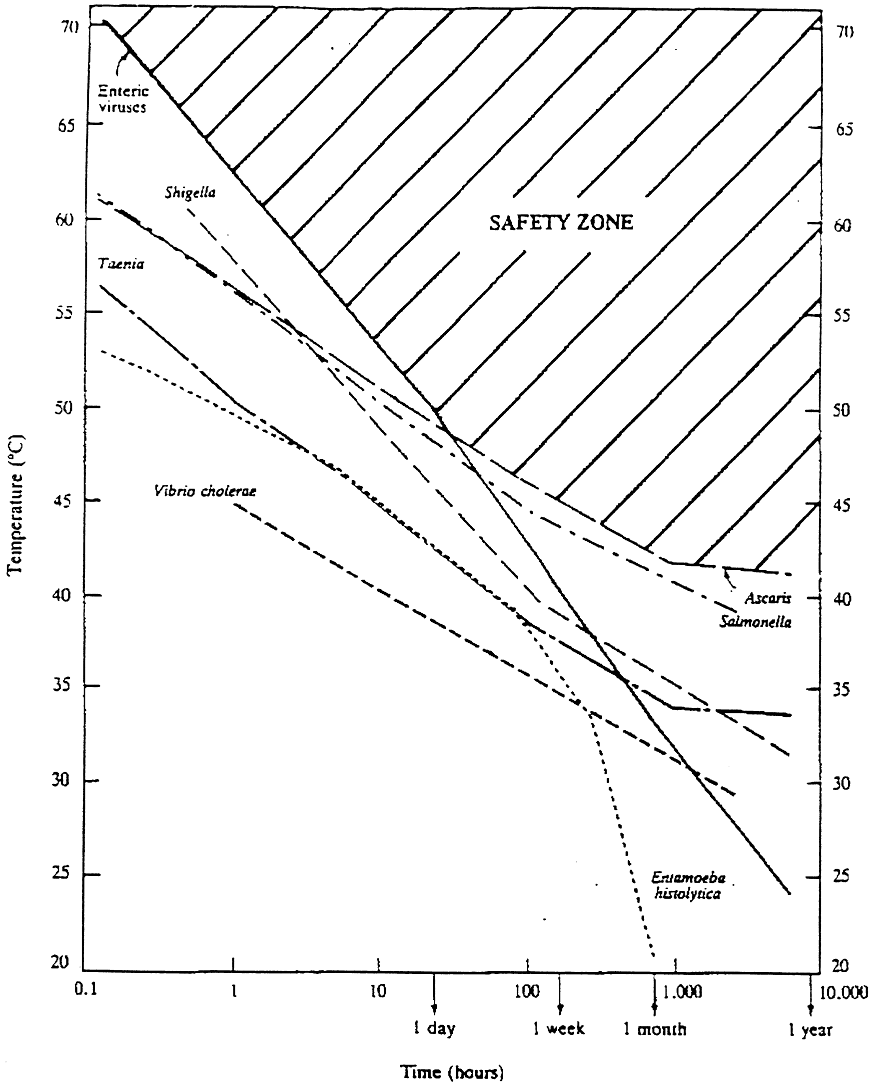

Fig. 4. Temperature–time relationships for safe water pasteurization (from [Feachem et al., 1983]). The temperature (°C) is on the vertical axis, and the time (h) is on the horizontal logarithmic axis. The hatched area in the upper right is the "safe zone" for all common pathogens. The lines represent safe zones for various specific pathogens.

comparison is confounded by wide cost ranges for some technologies and by the complexity of qualitative factors such as maintainability. For village-scale, slow sand filtration is most cost effective but requires significant low-cost labor. Chlorination dosing plants and UV are also relatively inexpensive village-scale approaches, both requiring pretreatment to reduce turbidity and filter cysts and worm eggs. Chlorination requires a continual supply of chlorine and trained operators. UV hardware is very simple and quick to implement but requires access to technical infrastructure for parts and maintenance. For home-scale, boiling has no capacity cost but has very high fuel and labor costs. Home filtration is low in first cost and utilizes indigenous materials and labor, but it is costly because of frequent replacement and is subject to failure from poor workmanship or unobserved cracks. Home filtration devices have an especially large cost range. The potential PV-powered UV unit with prefiltering would be convenient for homes with piped supply because it is an "on demand" system requiring no additional storage containers; its treatment cost is linearly dependent on assumed draw volume.

Solar pasteurization might be an option on both the village scale and the household scale. Household usage is the more likely market because village-scale alternatives have much lower treatment cost. Existing solar devices have water disinfection costs that are an order of

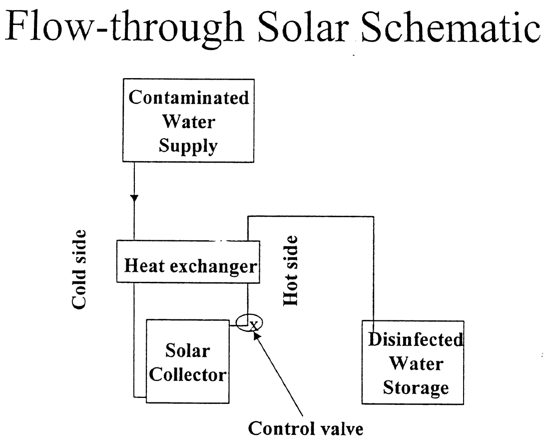

Fig. 5. A schematic for solar pasteurization. Heated water enters the counterflow heat exchanger from the collector outlet, exchanging heat with the cold incoming water. The control valve regulates the flow so that the desired pasteurization temperature is reached. The collector capacitance is designed to provide sufficient residence time at maximum flow rate.

magnitude less than boiling. Solar thermal pasteurization with existing manufactured devices costs more than the remaining alternatives but is highly effective and lowest in maintenance (assuming for metallic systems that freezing and scaling issues are eliminated by proper site analysis before deployment). By assuming a unit area productivity (200 l/m^2/day was used here) and equating the life cycle disinfection cost of solar pasteurization with the best competition, unit area cost goals can be derived (Burch and Thomas, 1998a). For village-scale treatment, the treatment cost with slow sand filter and with UV+PV+filter is about 3 ¢/m^3 and 14 ¢/m^3, respectively; the solar cost goal is about \$18/m^2 and \$84/m^2, respectively. For home-scale, the treatment cost with the potential UV+PV+filter system is about 63 ¢/m^3; the corresponding solar cost goal is about \$380/m^2. Existing metallic hardware could possibly achieve the latter costs, with about a factor of two reduction to reach the home-scale goal. Potential thin film polymer systems (Burch and Thomas, 1998a) could achieve the home-scale goal, but could meet the UV village-scale goal only with very low mark-ups for profit and distribution. It is not conceivable that any solar product could compete with village-scale slow sand filtration. Polymer film durability is an unresolved issue, although some research is underway as in Burch (1997).

4. CONCLUSIONS

The water disinfection problem in developing countries is large and complex. There are a number of appropriate methods for water disinfection, each with advantages and disadvantages. On the village scale, slow sand filtration

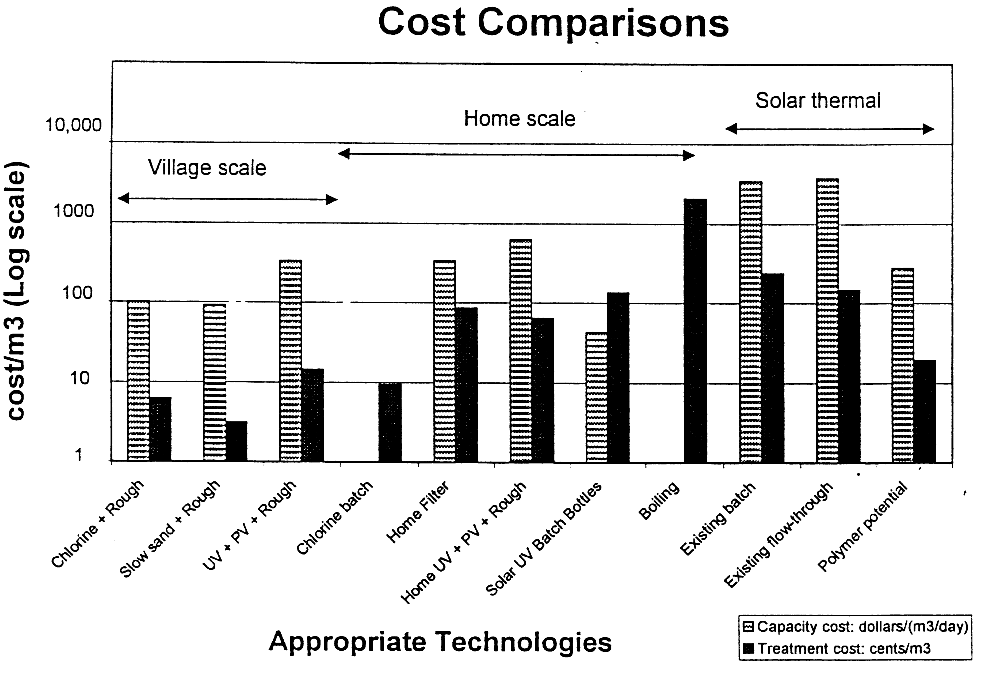

Fig. 6. Appropriate technology cost comparison. The y axis is $\log_{10}$ of the normalized costs. The hatched bar is the capacity cost in \$/m^3, which is the first cost divided by the daily output of the system. The solid bar is the normalized life-cycle treatment cost in ¢/m^3.

is widely recommended. Chlorine dosing plants will continue to be used. UV treatment is reasonably competitive if access to technical infrastructure for maintenance is adequate. On the household scale, chlorine will continue to be one of the most popular options for its low cost and residual disinfection. Home-scale filtration (perhaps combined with UV) holds promise of being effective and inexpensive.

Solar thermal pasteurization is effective and low in maintenance, but existing systems have higher life-cycle costs than most of the competition. For flow-through solar pasteurization costs to equal the chosen alternatives here, user cost goals are \$84/m^2 (village scale) and \$380/m^2 (home scale).

Acknowledgements—This work was supported by the U.S. Department of Energy, Office of Utility Technologies, Solar Buildings and Heat Program. The support of Frank Wilkins is gratefully acknowledged. Substantial assistance was provided by Ashok Gadgil for UV and Les Hamasaki and Will Hartzel for solar pasteurization.

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