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An Overview of Water Disinfection in Developing Countries and the Potential for Solar Thermal Water Pasteurization

Jay Burch
Karen E. Thomas

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
A national laboratory of the U.S. Department of Energy
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Executive Summary

This study originated within the Solar Buildings Program at the U.S. Department of Energy. Its goal is to assess the potential for solar thermal water disinfection in developing countries. In order to assess solar thermal potential, the alternatives must be clearly understood and compared. The objectives of the study are to: a) characterize the developing world disinfection needs and market; b) identify competing technologies, both traditional and emerging; c) analyze and characterize solar thermal pasteurization; d) compare technologies on cost-effectiveness and appropriateness; and e) identify research opportunities. Natural consequences of the study beyond these objectives include a broad knowledge of water disinfection problems and technologies, introduction of solar thermal pasteurization technologies to a broad audience, and general identification of disinfection opportunities for renewable technologies.

Waterborne disease is a staggering problem. Several billion people drink water potentially contaminated with pathogens that cause a variety of diseases. There are approximately 2.5 billion cases of waterborne sickness per year, causing about 5 million deaths per year (mostly children). Variables that are relevant to water disinfection problems and potential solutions include:

- Local population density: urban, village, and dispersed single family
- Existing water supply: deep-sealed well, shallow unsealed or sealed well, surface waters
- Water treatment: acceptable, questionable, or none
- Water pathogens: bacteria and viruses are ubiquitous, but protozoa and worms are localized
- Water turbidity: clean well water to "dirty" river water
- Water use: from several to several hundred liters per day per person
- Hygiene and washing practices: dependent on water supply and culture
- Availability of electricity: reliable, questionable, or none
- Local labor cost
- Income
- Infrastructure issues: varying access to supplies; training for operation, maintenance, and repair; and organizational support
- Education: implications for operation and maintenance of complex technologies
- Awareness of disease (the fecal-oral cycle): affects motivation to invest in and maintain water treatment.

Desired data are not readily available. The market segments of interest here are those with smaller volume/day demand (less than 25 m^3/day), including villages, and both dispersed and urban single family. Many authors believe that, for this market segment, the infrastructure issues are foremost in choosing the appropriate technology.

Water pathogens include bacteria, viruses, protozoa, and worms. Bacteria and viruses are readily treated with chemicals and ultraviolet (UV) light, but smaller bacteria and viruses are too small to be mechanically filtered. Protozoa and worms are larger and more easily filtered mechanically; however, they are resistant to chemicals and radiation. Turbidity in water allows viruses and bacteria to escape chemical and ultraviolet treatments. Water turbidity must be reduced by filtering to acceptable limits before chemical and ultraviolet techniques can be effective. Thus, chemical and UV treatments are almost always combined with filtering designed to reduce water turbidity to ~5 nephelometric turbidity units.

Disinfection methods appropriate for smaller-scale markets in the developing world include chlorination (dosing plant and batch processes), oxidant generation from electrolysis, slow sand filtration, household filtration, UV irradiation (from both sunlight and UV bulbs), boiling, and solar thermal pasteurization. These technologies are described, with emphasis on characterizing lesser-known solar thermal techniques. Solar thermal pasteurization includes batch and continuous-flow devices. Commercial devices using domestic hot-water technology have recently become available. To determine if there is a potential role for solar thermal techniques, technologies are compared on the basis of economics and appropriateness.

Principal economic comparison indices are the life-cycle water treatment cost per unit volume and the capacity cost (first cost per unit volume capacity). Technology costs reported in the literature vary widely (factors of two or more). Cost estimates provided here are considered approximate averages that could vary more than a factor of two in particular cases. Appropriateness comparison is based on assessment of effectiveness and maintenance needs. Maintenance needs are broken down into need for supplies; need for skilled labor to operate, maintain, and repair the system; and need for unskilled labor for operation and maintenance.

Economic comparison of selected technologies is summarized in Figure 1. Recently emerging solar thermal pasteurization systems have a high cost compared to the village-scale technologies. On the home scale, boiling has no capacity cost, but has a very high treatment cost because of high fuel costs. Existing solar devices have a water treatment cost of an order of magnitude less than boiling.

Appropriateness comparison is difficult but critical in choosing a technology. Chlorination requires a continuing supply of fresh chemicals. Batch chlorination is very easy but only moderately effective. (Cysts, eggs, and high turbidity present problems that require filtering.) Chlorine-dosing devices in treatment plants require trained operators and increase in complexity with the size of the system. Water pretreatment with roughing filters is usually done in dosing plants. Slow sand filters are effective and low cost but require lots of maintenance and construction labor. Pretreatment with roughing filters is usually required. Household filtration units are moderately effective; however, they require consistent maintenance and are prone to failure from cracking and problems with bacteria and viruses. Batch UV sunlight methods are emerging that are very low cost and easy to use but are very small scale, moderately effective, and need further study. UV lamp techniques are moderately simple; however, high turbidity or cysts/eggs require filtering. The devices require access to infrastructure for bulb and power supply maintenance. Water boiling is common and effective but is extremely costly and laborious. Solar thermal water treatment costs are relatively high with current technology. For solar thermal pasteurization systems with metallic passageways, maintenance considerations might include scaling and freeze damage. These issues should be taken as restrictions on suitable sites, rather than as maintenance problems. Solar thermal is inherently very low in maintenance if these restrictions are followed. Solar thermal pasteurization is extremely effective against all pathogens, and does not require substantive filtering before treatment.

Solar thermal pasteurization tends to cost more than the alternatives, but is the most effective and (in some markets) requires the least maintenance. It is unclear whether appropriateness advantages will overcome cost disadvantages. Economic assessment is uncertain because solar thermal pasteurization is an emerging technology that has not yet been cost optimized to the extent that other technologies have. If costs of $\$380/m^2$ could be attained, home-scale use would be competitive with the best home filter and UV/photovoltaic (PV) system. If costs of $\$90/m^2$ could be achieved, village-scale application would become cost competitive with PV-driven ultraviolet techniques.

4.3.3 Photocatalytic Disinfection

Photocatalytic disinfection is mentioned because it may likely be a useful approach in the near future. The photocatalytic process is still at the laboratory stage of development for disinfection but has been demonstrated to be effective on the pilot scale for removal of hazardous organic compounds from water and air (Blake 1994) and for disinfection of certain bacteria (Cooper 1997).

The basis of photocatalytic oxidation (PCO) differs from the action of the direct-acting UV systems discussed above. In photocatalysis, a photon incident on a catalyst initiates a chemical reaction producing a useful oxidant. Microorganisms are susceptible to damage from the action of reactive oxygen species, which include hydrogen peroxide (H_2O_2), superoxide ion (HO_2^-), hydroxyl radical (OH), and singlet oxygen (a form of electronically excited O_2). The first three are formed when a semiconductor, such as titanium dioxide in contact with water and air, is irradiated with light having a wavelength shorter than 385 nm. Singlet oxygen is formed when dyes such as methylene blue in water absorb visible light in the solar spectrum and transfer the energy to dissolved oxygen (Blake 1994). These processes were shown to kill a variety of bacteria and some viruses in water. The singlet oxygen process was demonstrated on the pilot scale to be effective in killing fecal coliform bacteria in secondary waste treatment effluent using sunlight.

With semiconductor catalysts such as titanium dioxide, the photon energy must be above the semiconductor band gap for the reaction to proceed. PCO can be driven by either UV lamps or sunlight. With UV lamps, PCO appears to be a natural and useful enhancement of the existing UV hardware. In addition to enhancement of direct UV, PCO would also lead to destructive decomposition of organic contaminants (Cooper 1997). With sunlight, these techniques may allow a larger portion of the sunlight spectrum to be effective compared to direct UV. Current catalyst research may enable use of higher wavelengths than those of the well-studied titanium dioxide catalyst (Goswami 1997). Techniques for stably coating titanium dioxide on thin plastic films were demonstrated at costs under $0.20/m^2 (Taylor 1997), which may lead to inexpensive and practical reactor designs.

4.4 Pasteurization (Thermal Disinfection)

Thermal sterilization of liquids (e.g., water and milk) is termed "pasteurization" after Louis Pasteur, who first articulated the fundamental germ basis of infectious diseases in the 19th century. Pasteurization by boiling of water has long been recognized as a safe way of treating water contaminated with enteric pathogens. Although some bacteria can survive even boiling temperatures (leading to autoclave temperature requirements of 120°C for sterilization of surgical instruments, for example), none of the disease-causing enteric pathogens survive boiling. In fact, pasteurization can take place at much lower temperatures, depending on the time the water is held at the pasteurization temperature T_p. Time decreases exponentially with increasing temperature. A semi-log plot of required time versus temperature is shown in Figure 4.4-1 (Feachem et al.1983). Viruses are generally the hardest to kill and essentially set the line of acceptable minimum time-temperature pasteurization domain. It is not considered common knowledge that boiling is not necessary; this may be a significant market impediment for solar thermal systems (Hamasaki 1997; Hartzell 1997).

There are two classes of pasteurization systems: batch and flow-through. In a batch process, the water in a container is brought to an appropriate temperature for appropriate time and then "removed" from the process. In a flow-through process, a continuous flow of water (usually via temperature-control valving) proceeds through a heating process, usually followed by a heat exchanger. The heat exchanger recovers heat of pasteurization, which is important for reducing the effective cost of treatment. The valving and heat exchanger increase product cost, but also greatly increase throughput; this tends to significantly lower the cost/volume compared to batch processes.

Section 4.4.1 describes batch pasteurization powered by fossil fuel, whereas Section 4.4.2 describes flow-through, fossil fuel-powered pasteurization. Section 4.4.3 describes solar-powered pasteurization systems, including three designs of batch systems and three designs of flow-through systems. Section 4.5 describes solar systems that perform multiple heating functions.

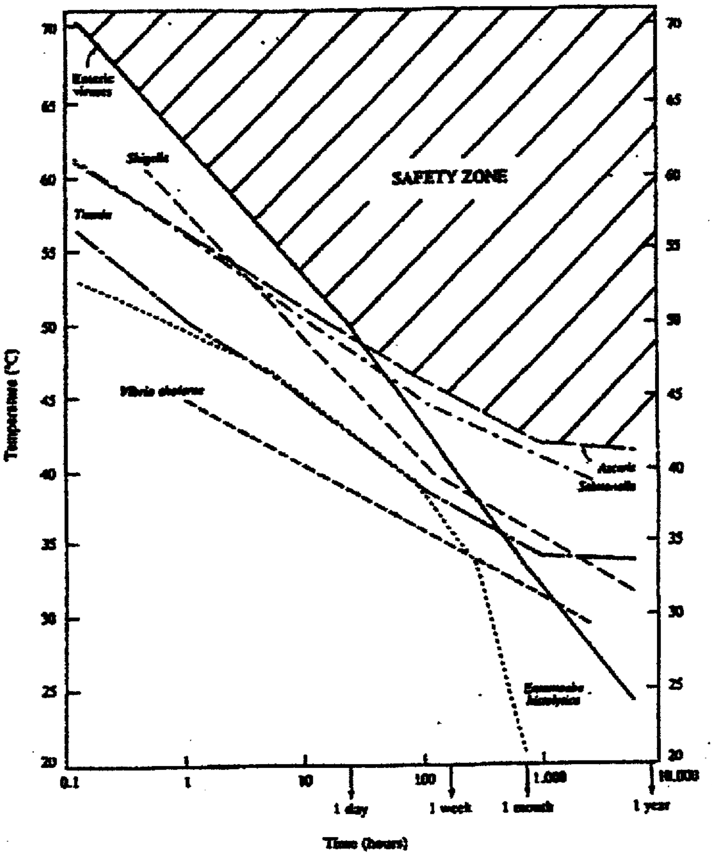

Figure 4.4-1. Temperature-time chart for safe water pasteurization (Feachem et al. 1983).

4.4.1 Fossil Fuel Heating/Batch Processes: Water Boiling

Cost

For simple small-scale boiling over an open flame, there is no incremental first cost, and dominant costs are for fuel (if fuel is purchased) and labor (both for attending and for fuel gathering when not purchased). We disregard such costs as vessel maintenance and replacement, health costs from polluted indoor air, deforestation, and other indirect costs. Fuel costs are generally high, although dedicated biomass processes could have moderate costs. The cost of fuel purchased has been estimated at $0.02/L (Andreatta 1994) and at $0.005/L (see Appendix H). When "free" fuel is gathered, the cost is in time and is difficult to quantify with any precision. It is not uncommon for women to spend several hours per day gathering fuel to cook with and boiling small batches of water (Feachem et al. 1977). This is partly because of the long distances one must travel to reach fuel. The estimate in Table 4-1 is based on the assumption of one hour of low-skill time ($0.05/hour) to gather fuel to disinfect 20 L (5 gal). Gathered fuel is cheaper, if labor is not valued highly. If labor is $0.50/hr, the cost of fuel becomes higher than that of purchased fuel. The second issue is the labor cost of attending the batch process. We assumed 20 minutes for a single batch of 20 L.