# EFFICACY OF CHEMICAL WATER TREATMENT TECHNOLOGIES IN THE BACKCOUNTRY

By Erica McKenzie and Dr. Ryan Jordan

Safe drinking water is a principal need of humans, and as such, post-Roman civilizations have devoted a large amount of resources to providing potable water to their citizens. Ironically, while water is essential for survival, it can also serve as a carrier and delivery method for many waterborne pathogens. These include protozoa, bacteria, and viruses that render intestinal disease symptoms that inspire prayer to unseen gods and plumbing systems.

Protozoan organisms are popular targets of water treatment technologies. Giardia and cryptosporidium outbreaks have both occurred in major U.S. municipalities, and occupy a high throne as perceived threats to backcountry water users. However, recent scientific thought leaders in this area seem to be downplaying the real significance of protozoan pathogen risk in backcountry waters (to the dismay of portable water filter manufacturers). Viruses and bacteria are gaining increased attention, and years of stock use and grazing in the western U.S. backcountry appears to be resulting in increased prevalence and risk of bacterial pathogens resulting from fecal contamination from stock animals. *Enterobacter* and *Enterococci* spp., two bacterial pathogens of fecal origin known to cause intestinal distress ranging from mild stomach aches to severe vomiting and diarrhea, can be found in both lakes and streams of the Pacific Crest Trail and Continental Divide Trail, with particular hot spots in areas popular for equestrian travel or grandfathered wilderness grazing. Areas close to our home in Montana that are known for significant risk include Grand Teton National Park, Wyoming Wind River Range, Bob Marshall Wilderness, and Yellowstone National Park.

**Viruses and bacteria are gaining increased attention, . . .**

This article focuses primarily on the role of pathogenic bacteria in backcountry water, and addresses treatment efficacy against bacteria.

Waterborne bacteria have the ability to live either on their own as free-floating planktonic bacteria, or in a community of cells adhering to a solid surface—a *biofilm*. It has long been recognized that the biofilm mode of growth is the normal mode by which bacteria exist in the environment. A far greater fraction of a water's bacterial population lives attached to slimes on stream and lake beds, as well as less visible biofilms floating at the water surface and attached to tiny particles suspended in the water.

Biofilms have some unique and interesting effects on its member microorganisms. First, a microorganism will frequently change its morphology and phylogeny when it assimilates into the biofilm. An example of a morphological change is the loss of flagella, cilia, or other such modes of motility. Second, members of the biofilm create an extra cellular matrix that not only helps attach them to the solid surface, but also provides an easy means of intercellular, interspecies communication. More important, the matrix resists penetration of chemicals. The organisms in a biofilm are more difficult to kill than planktonic organisms. This resistance allows a biofilm to harbor and protect pathogenic microorganisms, including not only bacteria, but also viruses and protozoa.

In natural waterways, greater than 99% of bacteria exist in biofilms. Remarkably, until only a few years ago portable water treatment technology manufacturers in the outdoor industry have been completely unaware of biofilms. A series of interviews we conducted in 2001 indicated that most outdoor industry water treatment technology manufacturers either had no idea what a biofilm was, or if they did, they were unable to understand the impact that biofilm bacteria had on their technology. In 2001, we interviewed more than 200 hikers along the AT in Georgia and North Carolina and in the major backpacking byways of Yellowstone and Grand Teton National Park. The number of hikers that had ever heard of a biofilm was zero.

As humans have pursued recreational activities in the backcountry and abroad, the outdoor industry has responded by producing portable water treatment technologies. Traditional methods include boiling and filtration. The industry is now also producing chemical purifiers based on technologies that have been employed in municipal water treatment plants for decades. Boiling remains an effective technology for killing both planktonic and biofilm cells. Filtration devices often clog as a result of direct filtration of biofilm cell clusters or slimes, even in apparently clear water. We have found that the storage of filtration devices or long-term use on the trail can result in biofilm growth in the filter element that can render it useless. Most backcountry users—and manufacturers—have long assumed that filter failure is a direct result of filtering silty water. A valid reason, indeed. But they have ignored the effect of biofilm growth in the filter element, a more common-than-not means of filter failure in the absence of significant silt, soil, or undissolved organic matter in the source water.

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Chemical purification relies on an oxidant's ability to destroy a pathogenic organism upon contact. A corollary of this is that as oxidant concentration increases, the kill-rate-per-unit time will also increase because there is more oxidant available to destroy the pathogens. However, each oxidant performs in a slightly different manner, and therefore occupies its own niche in destructive ability. This means that given the same conditions, oxidant A will not exhibit the same killing efficacy as oxidant B. Based on these two parameters, the killing efficacy is affected by both oxidant species and concentration.

The standard method that manufacturers use to address the killing efficacy of their chemical technology depends primarily on a long-outdated, "test tube" protocol that addresses the ability of the chemical to reduce the concentration of *planktonic* bacteria. These protocols completely ignore efficacy against biofilm, and are not realistic models for evaluating the effectiveness of a backcountry water treatment technology or method.

Thus, the objective of the study described herein is to address both oxidant type and concentration on killing efficacy of *biofilm* bacteria using a protocol that provides a more realistic model of backcountry water treatment.

**Efficacy Testing**

Biofilms are prevalent in nature, yet there are few statistics on the efficacy of various purification chemicals against them. Therefore, efficacy testing against biofilms was needed, and was accomplished by exposing a mature biofilm to a chemical purification treatment condition. Three different purification systems, each commercially manufactured, were used:

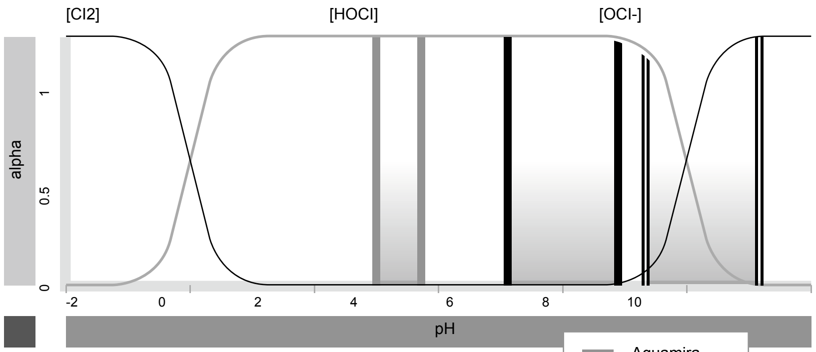


**Figure 1**: Chlorine species distribution for Aquamira, Polar Pure, and MIOX as a function of pH.

- Phosphoric acid-activated chlorine dioxide (distributed in kit form as Aquamira® by McNett™)
- Crystalline iodine (Polar Pure by Polar Equipment)
- Electrochemically activated mixed oxidants (MIOX™ by MSR®)

A rotating disk reactor system, now recognized by the American Society for Testing and Materials (ASTM) as a key component in a standard method for evaluating chemical disinfection efficacy, was used to grow biofilms in a moderate stress environment, simulating the stresses in a natural stream. This reactor, a 1000 ml Pyrex glass-type cylindrical beaker with an outlet at 250 ml, contained a rubber disk that housed six polycarbonate cylinders known as *coupons* on which biofilm bacteria were allowed to grow. This simulated biofilm growth on surfaces in the environment. The reactor system was placed on a magnetic stir plate, causing the rubber disk and coupons to spin. In order to sample the reactor, a coupon could be extracted and the biofilm scraped for quantification.

This system was inoculated with *Pseudomonas aeruginosa,* which was selected for use because of its prevalence in natural waterways and its ability to form a healthy biofilm. The bacteria were fed by a continual flow of low-nutrient broth to encourage growth. After the biofilm was established, a coupon was exposed to a treatment condition and then sampled to determine efficacy. Treatment duration and concentration were based on manufacturer recommendations.

**Biofilm Results**

The pH of each of the chemical purification systems was determined with a pH probe. The results were plotted on a chlorine species distribution diagram, indicating what oxidant was primarily formed for each of the oxidant systems (Snoeyink, 1980).

As figure 1 demonstrates, Aquamira results predominantly in hypochlorous acid. Hypochlorous acid is considered to be a better biofilm disinfecting agent than either $Cl_2$ or OCl- because of its ability to penetrate the biofilm matrix, whereas $Cl_2$ and OCl- react more strongly with matrix components and may never reach the depth of the biofilm where active cells are found. If Polar Pure was made up of a chlorine species instead of an iodine species, it would also exist predominately in the form of hypochlorous acid and might react similarly to Aquamira. However, it is not a chlorine species, so this assumption cannot be made. In fact, we have some anecdotal evidence from laboratory studies that indicate quite the opposite: that iodine species are ineffective at penetrating the biofilm matrix. MIOX, on the other hand, is a chlorine species, and exists as a combination of hypochlorous acid and hypochlorite. As previously stated, hypochlorite is considered a weaker disinfectant than hypochlorous acid. Therefore, given the same concentration of oxidant as free chlorine, one would expect Aquamira to be more efficacious than MIOX.

The rotating disk reactor standard deviation, as reported by ASTM (ASTM E2196-02, 2001) is Log 0.5. The standard deviation

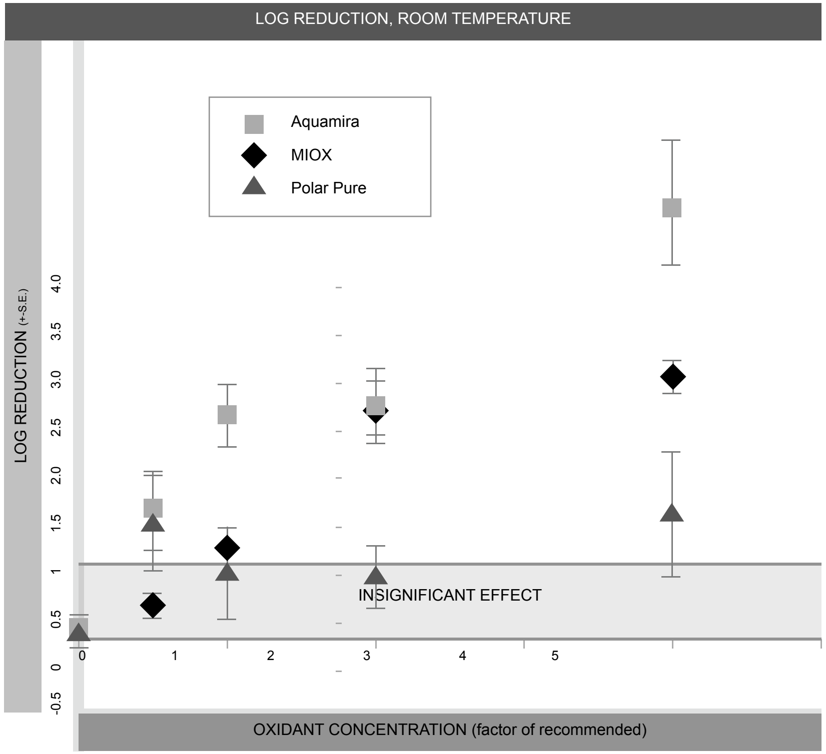


**Figure 2**: Biofilm killing efficacy by Aquamira, Polar Pure, and MIOX. Higher values on the Y-axis indicate better killing.

of all control coupons for these experiments was Log 0.42, verifying that the sampling procedure followed herein was sound. If a sample exhibits an efficacy of less than Log reduction 0.5, it was considered insignificant. Log reduction is a mathematic way of representing a factor-of-10 decrease and is usually employed when large numbers (such as bacterial populations) are being considered. A Log reduction 1.0 indicates that only 10% of the original population still remains. For example, if there were 100 originally, then 10 would remain. A Log reduction 2.0 means that 1% remains, and a Log reduction 3.0 means 0.1% remains, etc. The results of this procedure, for rotating disk reactors operated at room temperature, are highlighted in figure 2.

Owing to the method's standard deviation of Log 0.5, Polar Pure's effect at both the recommended and double the recommended concentrations were insignificant. The effect of half the recommended strength of MIOX was also insignificant. The efficacy of Aquamira at the manufacturer's recommended concentration was greater than that of both MIOX and Polar Pure—the two of which can be considered to exhibit similar levels of efficacy. MIOX and Aquamira continued to increase in efficaciousness with increasing concentration, while Polar Pure fluctuated and never reached a Log reduction of 1.0. At double the recommended concentration, Aquamira and MIOX presented similar efficacy, but Aquamira is considerably more efficacious than the MIOX at quadruple and at half the recommended concentration.

From this information, it can be concluded that Aquamira was the most efficacious oxidant among these three purifiers at killing biofilm bacteria in the experimental conditions studied herein. Aquamira not only provided the greatest destruction potential, it did so in the shortest treatment period. Additionally, chlorine dioxide had the least amount of oxidant measured as free chlorine, as can be seen in table 1.

MIOX has more than six fold the oxidant concentration of either of the other systems, and requires the greatest treatment time. This indicates that the oxidants in the MIOX system, when considered solely on oxidant concentration, might not have been as efficacious as those in the chlorine dioxide system or iodine systems in the experimental systems presented herein.

## Time-Concentration Planktonic Results

Efficacy is affected by oxidant concentration and treatment duration, and it is often assumed that the relationship between those two variables is roughly linear. This means that for the same efficacy, as concentration doubles, the treatment duration is halved. Conversely, if the oxidant concentration is halved, the treatment duration must be doubled. An attempt was made to determine a concentration-time curve for each oxidant system using planktonic bacterial suspensions. The results of these experiments did show a reduction in bacterial counts from

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| Concentration (factor of recommended) | Aquamira [Cl] 0 | Aquamira [Cl] f | Polar Pure [Cl] 0 | Polar Pure [Cl] f | MIOX [Cl] 0 | MIOX [Cl] f |
|---|---|---|---|---|---|---|
| **0.5** | 0.07 | 0.11 | 0.15 | 0.13 | 1.83 | 1.57 |
| **1** | 0.22 | 0.22 | 0.45 | 0.39 | 4.20 | 4.14 |
| **2** | 0.65 | 0.50 | 0.69 | 0.62 | 8.00 | 7.65 |
| **4** | 1.41 | 0.97 | 2.41 | 1.71 | 16.10 | 16.35 |

**Table 1**: Initial (0) and final (f) oxidant concentration as free chlorine (Cl).

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## Efficacy of Chemical Water Treatment

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approximately 350 colony forming units to virtually zero in five minutes or less. This is less than the recommended treatment time for all treatment formulations at 1x, 2x, and 4x recommended treatment concentrations.

RECOMMENDED TREATMENT TIME

- Aquamira: 15 minutes
- Polar Pure: 20 minutes
- MIOX: 30 minutes

**Temperature Results**

An equation developed by H. F. R. Reijnders, accounting for pH and temperature, was employed to convert free chlorine to hypochlorous acid. Because hypochlorous acid is a superior disinfectant, it can be considered a relative indicator of efficacy (table 2).

Because Aquamira and Polar Pure have a lower pH, they experience little to no change in hypochlorous acid concentration with the corresponding temperature change. On the other hand, MIOX has a higher pH, causing the hypochlorous acid concentration change to be mathematically significant. This idea was correlated to the results of the chlorine species diagram in figure 1. This indicated that the Aquamira and Polar Pure systems would react at similar rates at both $22^{0}$C and $4^{0}$C. Conversely, MIOX would proceed at a slower reaction rate at the colder temperature because more of the oxidant

| Concentration (factor of recommended) | [Cl] (mg/L) | pH | [HOCl] @ 22C (mg/L) | [HOCl] @ 4C (mg/L) |
|---|---|---|---|---|
| **Aquamira x 0.5** | 0.07 | 3.71 | 0.07 | 0.07 |
| **1** | 0.22 | 3.38 | 0.22 | 0.22 |
| **2** | 0.65 | 3.29 | 0.65 | 0.65 |
| **4** | 1.41 | 2.98 | 1.41 | 1.41 |
| | | | | |
| **Polar Pure x 0.5** | 0.15 | 6.83 | 0.14 | 0.14 |
| **1** | 0.45 | 6.4 | 0.44 | 0.43 |
| **2** | 0.69 | 5.22 | 0.69 | 0.69 |
| **4** | 2.41 | 5.78 | 2.40 | 2.39 |
| | | | | |
| **MIOX x 0.5** | 1.83 | 7.16 | 1.62 | 1.52 |
| **1** | 4.2 | 7.75 | 2.79 | 2.35 |
| **2** | 8 | 8.61 | 1.72 | 1.19 |
| **4** | 16.1 | 8.95 | 1.79 | 1.19 |

**Table 2**: Temperature effects on hypochlorous acid concentration.

concentration would exist as hypochlorite and less as hypochlorous acid.

In general, the efficacy of the chemical purifiers increased as the oxidant concentration increased. Aquamira, a chlorine dioxide system, proved to be the most efficacious system against biofilms, returning statistically significant results when compared to other systems at the half, full, double, and quadruple factors of manufacturer recommended concentrations. The mixed oxidant system MIOX also proved to be efficacious against biofilms at double and quadruple recommended concentrations, minimally efficacious at the recommended concentration, and it did not present a significant effect at half the recommended concentration. Polar Pure proved to be the least efficacious of the three systems, never exceeding Log reduction 1.0 and only having a significant effect at two of the four tested concentrations.

When the oxidant systems were applied to planktonic systems, all treatment conditions proved efficacious. The difference between the results was virtually nonexistent based on the collected data.

This study investigated a narrow set of operating conditions in the laboratory, using a model experimental system that is undoubtedly limited in its ability to predict all field conditions. However, because of the controlled environment, we were able to isolate two important variables—planktonic versus biofilm cell type, and oxidant dose relative to manufacturer recommendations—to determine the relative ability of each treatment system to reduce concentrations of biofilm bacteria over a range of oxidant dosages. Consequently, since bacteria in natural waters exist primarily in a biofilm mode of growth, rather than planktonic, it is therefore no great stretch of the imagination that the same relative efficacy of the methods studied herein might be validated by investigating their performance in natural waters, as well.

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The reader, of course, should be cautious. We did not address key factors that are important in the natural environment, including the presence of turbidity and organic matter, which can have a profound impact on treatment efficacy (usually reducing efficacy dramatically). Consequently, this study is meant to provide only one piece of data that a consumer might use to make an informed decision about which treatment method to choose for a particular application, recognizing that the complexity of such decisions can be further confounded by factors such as cost, ease of use, packed size, weight, and susceptibility to marketing claims by manufacturers.

### About the Authors

Dr. Ryan Jordan holds a Ph.D. in biofilm engineering from Montana State University's world-renowned Center for Biofilm Engineering (CBE). Dr. Jordan served as a senior research engineer at CBE for seven years, focusing his efforts on programs related to backcountry water research, bacterial growth in next-to-skin athletic performance textiles, environmental remediation, and anti-infective coating technologies for biomedical devices. Dr. Jordan is the cofounder and publisher of *Backpacking Light Magazine*, serves on the board of directors for the Biofilm Institute, and is a senior partner of Cytergy, LLC. This research remains ongoing, and Dr. Jordan continues to be an active consultant to water treatment system manufacturers interested in optimizing their products to be efficacious against biofilms in natural waters.

At the time of this research, Erica McKenzie was a scholarship student working with Dr. Jordan, Dr. Anne Camper, and Darla Goeres, under the National Science Foundation's Research Experience for Undergraduates (REU) program at the CBE.

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### Suggested Reading

American Water Works Association. Water Quality and Treatment: *A Handbook of Community Water Supplies, Fourth Edition* (New York: McGraw-Hill, Inc., 1990).

ASTM E2196-02. "Standard Test Method for Quantification of a Pseudomonas aeruginosa Biofilm Grown with Shear and Continuous Flow Using a Rotating Disk Reactor" (ASTM International, 2001).

Hamilton, Martin A., and Becky R. Herigstad. "Calculating the Log Reduction and the Standard Error for Disinfection Studies—Formulas and Numerical Examples" (Center for Biofilm Engineering, 1998).

Havelaar, A. H., et al. "Mycobacteria in Semi-Public Swimming Pools and Whirlpools," National Institute of Public Health and Environmental Hygiene (1985).

Snoeyink, Vernon L., and David Jenkins. *Water Chemistry* (New York: John Wiley and Sons, 1980).