Technical summary of filtration, microfiltration and ozone treatment

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Executive Summary

Filtration, microfiltration and ozone contribute significantly to disinfection of drinking water. Filtration and microfiltration will be shown to be the workhorse of this disinfection system.

Introduction

The Living Waters for the World (LWW) board utilizes both filtration and ozone to treat water for drinking and cooking. Prior to the expansion of work in the Yucatan, we used a 2 tank, 2 pump system to prepare ozonated and filtered water, which was subjected to a final treatment with bleach to assure the water remained disinfected after bottling and at the homes of users. We found that our partners were not adding the bleach because of the taste and odor it imparts to the water. Taste and odor problems could arise because people are not used to having chlorine in their drinking water, or because they were adding too much bleach to the water; this was not totally clear which, or both, were the reason.

It was decided in 2004 to abandon the addition of bleach to the tank as a final disinfectant and to look for a way to use ozone to accomplish the same thing. It should be noted that, although bleach is not added to the tank, all bottles are to be washed with bleach as described in the IOM, and then rinsed with ozonated water prior to filling. So, ozone is used to give the water a final disinfecting treatment prior to filling the bottles. This is accomplished by the addition of an ozone recirculation step prior to and during the bottle washing and filling process.

As the system has been simplified, first by eliminating chlorine and then by developing a 1 tank, 1 pump process, the discussion of the relative contributions of filtration and ozonation to the disinfection process has intensified. This paper is intended to lay out these issues, backed by references and quantitative data, so that the Technical Committee can act on the proposals of the Design Team. These proposals are not included here, as this is intended to be a technical support document to facilitate the decision-making process.

First, it needs to be made clear that the LWW system is a disinfection system, not a sterilization system. This is true of all drinking water treatment systems. Disinfection is the removal or deactivation of most (99.9 to 99.9999%) disease causing organisms in the water. Sterilization is the removal or deactivation of 100% of these organisms. Disinfection is effective in preventing human illness because illness comes from a combination of the virility of the organism, sensitivity of the individual and the viable organism dose. Not all organisms in the water will be viable.

The steps in drinking water production are:

- use a pristine source of water
- disinfection (usually chlorine)
- protect water from reinfection in the piping system
  - pressure
  - chlorination

Depending on the source of water, chlorination can be preceded by sedimentation, These practices in the U.S. result in the safe production of millions of gallons of drinking water per day with no adverse effect on people. However, it should be noted that illness outbreaks do occur and usually relate to a breakdown in the treatment process, or contamination of water by leakage, etc. after the water leaves the treatment plant. Many times, the most affected individuals are those who are elderly, the very young, and others with suppressed immune systems.

As we know, where LWW is in active partnership, the water source is not always pristine and the standard system is designed to address those situations through the filtration and ozonation steps.

This paper will discuss two factors at play in the disinfection process of the LWW system;

- pathogen size and
- pathogen sensitivity to ozone.

Filtration

The filtration step is a physical separation of the microorganisms from the water by passing the water through a filter with pore sizes that are smaller than most microorganisms. Table 1 below gives a comparison of the sizes of various objects to help put the size of disease causing organisms into perspective. An interesting web site that gives an interactive display of these sizes is also available (http://www.cellsalive.com/howbig.htm).

Table 1 – Relative sizes of common objects

Particle	**Size, micron (µm)**
Beach sand	100 - >1000
Pin Point	80
Human hair	30-150
Giardia cysts	8-20
Cryptosporidium	2-4
Bacteria	0.2-30
Viruses	0.004 – 0.1

Bacteria and other microscopic organisms are usually measured in units of a micron, also called a micrometer (µm). A µm is one one-millionth of a meter. Also, 1 µm is 0.00004 inches. Most microorganisms of concern in drinking water treatment are 0.3 µm, or greater, in size, Table 2 below gives the sizes of some key microorganisms.

Table 2. Size and resistant forms of microorganisms found in wastewater[1]

Microorganisms	Size, **µm** **D=diameter** **L=length**	Environmentally resistant form	LWW treatment F = filtration O = ozone
Bacteria			
Bacilli	0.3-1.5 D x 1-10 L	Endospores or dormant cells	Dormant = F Live = F+O
Bacillus (E. coli)	0.6-1.2 D x 2-3 L	Endospores or dormant cells	Dormant = F Live = F+O
Cocci	0.5-4 D (spheres)	Endospores or dormant cells	Dormant = F Live = F+O
Spirilla	0.6-2 D x 20-50 L	Endospores or dormant cells	Dormant = F Live = F+O
Vibrio	0.4-2 D x 1-10 L	Endospores or dormant cells	Dormant = F Live = F+O
Protozoa:			
Cryptosporidium			
Oocysts	3-6 (spheres)	Oocysts	F
Sporozoite	1-3 W x 6-8 L		F
Entaboeba histolytica			
Cysts	10-15 D (spheres)	Cysts	F
Trophozoite	10-20 D (sphere)		F
Giardia lamblia			
Cysts	6-8 W x 8-14 L	Cysts	F
Trophozoite	6-8 W x 12-16 L		F
Helminths (worms)			
Ancylostoma (hookworm egg)	36-40 W x 55-70 L	Filariform larvae	F
Ascaris (roundworm egg)	35-50 W x 45 – 70 L	Embryonated egg	F
Trichuris (whipworm egg)	20-24 W x 50-55 L	Embryonated egg	F
Viruses			
MS2	0-.022-0.026	Virion	O
Enterovirus	0.020-0.030	Virion	O
Norwalk	0.020-0.035	Virion	O
Polio	0.025-0.030	Virion	O
Rotavirus	0.070-0.080	Virion	O

[1] Tchobanoglous, George, et al Wastewater Engineering: Treatment and Reuse, 4th edition, Metcalf & Eddy, Inc. 2003.

<u>The 50 and 5 μm filters and the 0.5 μm microfilter will be very effective at removing single cells of most bacteria and nearly all the protozoans and worms</u>. Filters come in several size cutoffs. Sand filters and diatomaceous earth filters, such as might be used in large drinking water facilities and pools/spas, respectively, can remove particles down into the range of about 20 μm and greater. This filtration is often assisted by addition of chemicals that cause smaller particles to coalesce into larger particles that are more likely to be caught in these filters. The LWW board includes a "trash filter" of 50 microns (μm), followed by a 5 micron filter designed to remove larger, suspended particles that would plug the next smaller filter that follows, and can be thought of as taking the place of the aforementioned sand and diatomaceous earth filters. This filtration also helps remove microorganisms that are attached to small particles of dirt, sand, algae, etc. suspended in water or that are growing together in multicelled colonies. The 0.5 μm microfilter is designed to remove single-celled microorganisms, hence the term microfilter.

The microfilter works through a combination of physical size exclusion and adsorption or adherence inside the microfilter. If one were to see a microscopic view of the 0.5 μm microfilter, it would appear sponge-like with many caverns throughout. Any organism that passes through the microfilter not only has to be small enough to fit through the 0.5 μm pore size, but also has to wind its way through a torturous path. The 0.5 μm microfilter used in the LWW board is about 1.5 inches thick. A 0.3 μm organism must travel the equivalent of 127,000 times its cell length (in a straight line, further in the torturous path) to get through the microfilter. Adsorption may also result in some reduction in viruses.

Most pathogens will not reproduce on the filters. Microorganisms that are pathogenic depend on the presence of very specific conditions in order to grow and cause disease. Those conditions are met inside the human body, which is significantly different from those present on the filters or on the microfilter.

Pathogenic organisms can, however, go into a dormant state that remains viable for many days, during which time they can cause infection if ingested or otherwise taken into the body where growth conditions are met. Some typical survival times for the dormant state of some pathogens are given in Table 3.

Table 3. Typical pathogen survival times at 20-30 C in Freshwater and Wastewater[1]

Pathogen	Survival time, days
Bacteria	
Fecal coliforms	<60, usually <30
Salmonella spp.	<60, usually <30
Shigella	<30, usually <10
Vibrio cholerae	<30, usually <10
Protozoa	
E. histolytica cysts	<30, usually < 15
Helminths	
Ascaris eggs	many months
Viruses	
Enterovirus	<120, usually <50

The longer a collection of dormant cells remain on the filter the less virulent they become. So, as new cells are trapped on the filter, older ones are inactivating. Accumulation of true pathogens on the filters is dependent on the volume of water processed and concentrations of pathogens in the water, and is not exacerbated by growth.

Not all bacteria in water are strict pathogens. It is the growth of these non-pathogenic organisms that can

(1) Plug the filter and microfilter cartridges.
These non pathogenic organisms can grow on any of the filter surfaces if presented with proper nutrients of nitrogen phosphorus and organic carbon, as found on carbon filters. In most drinking water supplies these nutrients are very limited, which will in turn retard growth of bacteria

If plugging of the filters or microfilter by biological growth becomes a problem, the source of water should be further evaluated for the presence of abnormally high organic carbon, nitrate and phosphate, which could be accelerating the growth of the non-disease causing organisms described above, and an alternative water source considered.

(2) **Contribute to potential health problems to those handling the cartridges.**
Some may cause diarrhea or other conditions if ingested in large amounts, will also grow.

Therefore, changing or otherwise handling the filter cartridges (including the trash, 50 µm filters, and the 0.5 µm microfilter) should be done practicing normal hygiene. This includes, washing with soap and disinfected drinking water after handling the filters. If this is done, the risk of becoming ill after handling the filters is minimal. This should be a topic of the training that takes place during the installation trip, and is discussed in the IOM.

These non-pathogens are the same organisms we are exposed to in the dust we inhale, and in the soil of our gardens, etc.

Chemical disinfection

<u>Chlorine:</u>

Historically, chlorine has fulfilled this role and chlorination of drinking water has saved literally millions of lives since its use began in the early 1900's and continues to do so today.

The down side of chlorine is its taste and the discovery in the 1970s that it reacts with organic compounds in the water to produce "trihalomethanes", such as chloroform, which have been shown to be carcinogenic. In the experience of LWW, the biggest problem has been one of taste. Users have been unable to adjust the dose sufficiently to achieve the necessary disinfection residual (0.5-1 mg/L free chlorine) resulting in overdose, but also may be rejecting the water on the basis of taste because they have no experience with chlorinated water. Thus, even the appropriate dose may be proving unacceptable in terms of taste.

Since the current operating philosophy is to not use chlorine, except for cleaning bottles, there will be no further consideration of chlorine in this paper.

Before discussing ozone, a concept for expressing comparative disinfection power and microorganism sensitivity is introduced.

<u>The Ct concept offers a means for determining disinfection potential for a chemical as well as a way to express the sensitivity of various microoganisms to different disinfectants</u>.

Ct is the concentration-time value for a disinfecting chemical and is expressed as the concentration of the chemical multiplied by the time that the organism is exposed to the given concentration. In its simplest, and most utilitarian, form Ct is the concentration in mg/L times the exposure time in minutes, and is expressed as mg-min/L.

$$Ct = C, \text{mg/L} \times \text{time, min.}$$

Thus, a chemical can achieve the same disinfection effectiveness by increased concentration at a shorter exposure time, or by increasing the exposure time at a lower concentration. But both time and concentration are integral to successful disinfection.

<u>Ozone:</u>

Ozone offers a good alternative to chlorine for disinfection. While ozone does not offer the residual protection – ozone reacts away in minutes versus chlorine in terms of hours – it does offer a more aggressive disinfectant towards microorganisms.

In the LWW board the exposure time is determined basically by the time the water spends in the ozone contact loop, which is the pipe length from the venturi to the time it enters the tank. There may also be some exposure time in the tank, but to date measurements have not detected a residual ozone concentration in the tank itself, but only at the immediate exit from the ozone contact pipe (see discussion below).

The ozone concentration is determined by the ozone production capacity of the Prozone PZII-2 (1 gram/ hr.) and the flow rate of water through the contact venturi and loop. The current board has been operated such that, during ozonation, water is pumped through the venturi, which is the only flow restriction. Under this condition, the flow rate is about 9 gpm. Thus, according to the calculation below:

Ct = ozone concentration x time, mg – min/L

and

C = ozone concentration:
C = 1 g/hr / 9 gal/min
C = (1000 mg/hr)/(9 gal/min x 3.7854 L/gal x 60 min/hr) = 0.49 mg/L

This is the MAXIMUM ozone concentration possible, assuming 100% transfer of ozone gas from the air stream into the water stream. The actual amount transferred is between 50 and 75%, or 0.24 and 0.37 mg/L. The only way to increase the ozone concentration, C, is to reduce the flow rate by restricting the pump flow, or by adding more ozone generation capacity.

Another sequence in which water is filtered and then ozonated in a single step where both microfilter and ozone venturi cause resistance to flow and the flow rate is reduced to 4.5 gpm, which would help increase the ozone concentration.

The length of the ozone contact loop and subsequent piping up to the tank determines the time of exposure. It is possible some residual remains in the tank, especially if the tank contents are recirculated through the ozone contactor multiple times. The contact loop is about 30 ft. and the pipe is 1 inch diameter. To determine the time of exposure the cross sectional area of the pipe need to be determined to calculate the velocity of water (at 9 gpm) through the contact loop.

Thus;

Area = $\pi \times r^2 = 3.14 \times (0.5)^2 = 0.79$ sq. inches x 0.000645 sq m/sq inch = 0.00051sq m.

The flow is:

Flow = 9 gal/min x 3.785 L/gal x 1 m^3/1000 L = 0.034 m^3/min

The velocity in the loop is thus:

velocity = 0.034 m^3/min / 0.00051 m^2 = 66.6 m/min

And the time in the 30 ft loop is thus;

time = 30 ft x 0.305 m/ft = 9.15 m x 1/66.6 m/min = 0.14 min

Now, combining the concentration and time:
Ct = 0.24mg/L x 0.14 min = 0.034 mg-min/L at 50% transfer, or if the ozone transfer is 75%, then;

Ct = 0..37 mg/L x 0.14 min = 0.051 mg-min/L.

So, the Ct for the current board (and also for previous boards since the ozone generator and flows have not changed) is between 0.034 and 0.051 mg-min/L. Table 4 below gives the Ct required to kill 99.9 to 99.99% of a given organism. Ct values will vary depending on the state of the cell; one adhering to a larger particle, or a group of cells held together by a slime layer, etc. will require a higher Ct than a new growing cell suspended in water.

Table 4. Ct ozone for example microorganisms

Organism	Ct for ozone	Number of passes required
E. coli	0.01[2]	0.2
Streptococcus faecalis	0.015[2]	0.3
Polio virus	0.1[2]	2.
Endamoeba histolytica	1[2]	20
Bacillus megatherium spores	0.3[2]	6
E. coli	0.02[3]	0.6
Giardia lamblia (cysts)	0.5-0.6[3]	11
Cryptosporidium	0.5-0.7[3]	11

The third column is the number of passes through the ozone loop, exposed to 0.37 mg/L ozone, it takes to inactivate 99.9 to 99.99% of the given microorganism. Note that the indicator organism, E. coli, is one of the more sensitive bacteria species, and that bacteria are in general more sensitive than are protozoans. It is interesting to note that E. coli is one of the more sensitive bacteria, but is generally used as the indicator organism for disinfection. Thus, it is possible to get a very low E. coli count, and still have viable pathogenic microorganisms present.

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[2] White, Clifford, Handbook of Chlorination and Alternative Disinfectants. 4th edition. John Wiley and Sons, Inc. New York.
3 World Health Organization guidance on ozone disinfection. See the WHO web page for drinking water disinfection. Document also attached as PDF file to this report. © 2004 World Health Organization. Water Treatment and Pathogen Control: Process Efficiency in Achieving
Safe Drinking Water. Edited by Mark W LeChevallier and Kwok-Keung Au. ISBN: 1 84339 069 8. Published by IWA Publishing, London, UK.

<u>Thus, while ozone is a much more powerful disinfectant than chlorine, the dose we are providing is inadequate to achieve significant disinfection on one pass of ozone.</u>

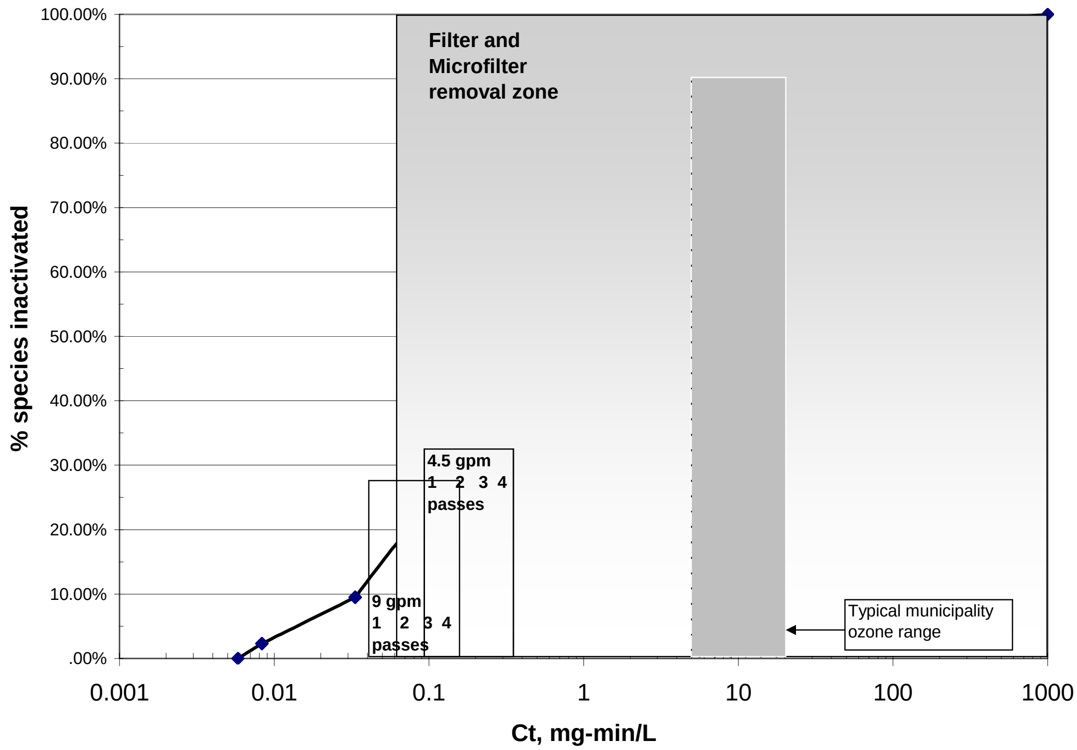
The effectiveness on various species of each of the treatment process, filtration, microfiltration and ozone, are summarized in Figure 1.

Current operation of the board calls for multiple passes of water through the ozone contact loop to increase the Ct by increasing the exposure time. Figure 1 illustrates the impact 1, 2, 3 and 4 passes through the ozone loop at 9 gpm and at 4.5 gpm will have on inactivating microorganisms. The Ct for several species of bacteria, protozoans, worms and viruses was ranked from lowest Ct to highest Ct, and plotted as Ct versus cumulative percent.[4,1,3] For the 9 gpm case, 1 pass inactivates approximately 10% of the tabulated species, at 2 passes, approximately 20% of species would be inactivated and so on. After 4 passes, about our maximum, about 23% of species are inactivated.

Reducing the flow to 4.5 gpm increases the ozone system Ct. A 1 pass treatment at 4.5 gpm inactivates about 21% of species, 2 passes inactivates about 28% of species and so on up to about 31% of species with 4 passes. The species represented by these fractions constitute the smaller single bacteria cells and viruses that are most sensitive and have the greatest chance of passing through the microfilter. However, aside from the viruses, most of these single bacteria cells are greater than 0.5 µm in size (Table 2).

[4] http://www.ozoneapplications.com/info/ozone_bacteria_mold_viruses.htm

Figure 1. Comparison of LWW Filter, Microfilter and Ozone treatment effectiveness on microorganisms.



The PZII-2 ozone generator has a set ozone delivery rate of 1 g/hr, so, unlike bleach where more can be added, we can't increase the dose the PZII-2, since the two lamp cartridges fix its ozone production rate. However, Prozone manufactures a PZII-4 that would double the amount of ozone dosed to the system, and larger arrays of lamp cartridges are also available.

In summary, although we haven't measured the ozone concentration, we can calculate the maximum possible concentration, and that proves to be 0.44 mg/L (at 9 gpm flow rate). This dose will be ineffective in a one pass treatment for a great many microorganisms. The fact that we perform a three pass treatment is helpful, but we are also very dependent on the 0.5 µm microfilter to remove the majority of harmful organisms.

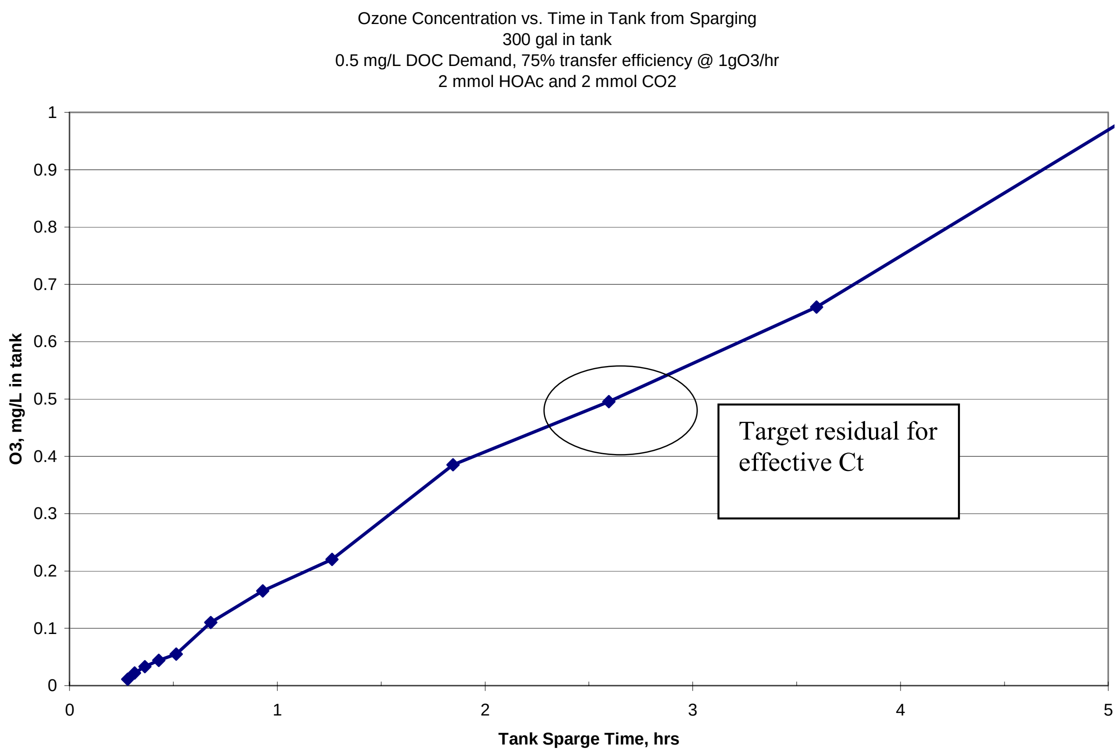
At the October 28, 2005 Technical Task Force work weekend, we measured ozone accumulation in a 2 gallon container into which the ozone tube was inserted. It took approximately 20 minutes to show a response on the ozone test strips at 0.3 mg/L. So, while the ozone strips do respond, it appears that their sensitivity below 0.2 mg/L is questionable. However, they appear to be able to detect 0.3 to 0.4 mg/L or higher.

During this same weekend, a test was done to determine the effect of ozone treatment alone on water. The system was operated at 9 gpm using the PZII-2, which gives a calculated maximum Ct of 0.03 mg-min/L. After 24 hours, the one pass, ozone-only treated water showed a positive pathoscreen result equivalent to the raw water result, indicating little disinfection had taken place in one pass. Visual observation of water in the roof tank indicated no change in the color, turbidity from the raw water. This result appears to support the Ct calculations discussed above.

Ozone addition to the tank could require up to 4 hours for effective disinfection. Figure 2 shows a plot of ozone concentration versus time for a full, 300 gal., tank. The curve was calculated based on the following premises.

- There is 0.5 mg/L organic carbon in the water that will react with ozone. This carbon must be reacted before ozone can accumulate for disinfection.
- The organic carbon does not completely react to carbon dioxide before ozone begins to accumulate.
- The ozone transfer efficiency from the gas bubbles to the water is 75%.

Figure 2.



Under these premises, it will take approximately 30 minutes to react with the organic carbon, and then a total of 2.5 to 3 hours to build up to 0.5 mg/L ozone concentration, which is recommended by NSF.[5]

Putting filtration and ozone together as water disinfection

The question has come up as to whether it is most effective to ozonate, filter and then ozonate for filling bottles, or to filter and then ozonate. The issues are given in the table

[5] Environmental Technology Verification Protocol. Drinking Water Systems Center. Protocol for Equipment Verification Testing for Inactivation of Microbiological Contaminants. by NSF, International in cooperation with the Environmental Protection Agency. 3/9204/EPADWCTR, Jan. 2003. http://www.nsf.org/business/drinking_water_systems_center/pdf/finalprotocoltps_microinact.pdf

below. In order to make such comparisons, the range of species effectively removed by microfiltration is indicated on Figure 2. The filter cutoff corresponds to the size of viruses and small single cell bacteria (very few species here) and is thus proportional to the Ct values shown. Thus, the most ozone sensitive species will not be caught efficiently by the microfilter.

Table 6. Operating sequence pros.

Sequence	Pros	Relevant data from this paper (rebuttal or support)
Ozone first, then filter	One pass ozone kills approximately the most sensitive 10% of pathogenic species.	Refer to Tables 4 and 5 and Figure 1 for Ct data on several pathogens. The "low kill" fraction puts live microorganisms into the tank.
	Pre-ozonation may enhance filtration (by Prozone).	This will assist in coagulation if ozone dose is high enough (most likely a > 1 mg/L concentration would be required). A second tank is required to perform this sequence of treatment steps.
Filter first, then ozone	Filters remove the majority of suspended particulates and most free microorganisms, keeping them out of the tank.	See Tables 1 and 2 that show microorganisms exceed 0.5 micron in at least one dimension.
	Ozone can be more effective after suspended particulates have been removed.	Viruses and single cell microorganisms that may escape the filter are the most sensitive to ozone and are more exposed after filtration. Filters may accumulate large amounts of live microorganisms: • may plug the filters

Sequence	Pros	Relevant data from this paper (rebuttal or support)
		prematurely • may present a hazard to workers changing the filters. This applies to all three filters.
One pass filtration and ozonation system.	Only water that has been both filtered, microfiltered and ozonated reaches the tank. Reduces the time in the production of drinking water by incorporating the ozone pass into the first step. Reduces flow rate to 4.5 gpm, which increases Ct for each pass.	

What does the industry do? In reading the literature, drinking water is usually treated with lime to coagulate and precipitate out suspended solids. It has been reported that this can actually remove 50 to 70% of microorganisms because they are either attached to the solids being removed, or are entrapped in the process of coagulation.[6,7] Many times, this is all that is done to drinking water before it is chlorinated and sent into the distribution system.

It is usually recommended that ozone be applied after filtration since filtration will remove particles that protect microorganisms as well as consume ozone.[3] This is usually the case because the ozone molecule is a much more effective disinfectant than the free radicals it forms upon decomposition. However, ozone can react with suspended solids and colloids and cause them to coagulate so that filtration is more effective. When ozone is used, contact times are usually in the 10 to 30 minute range[8]. This is for wastewater, which may be "dirtier" than typical drinking water, so contact times for drinking water could be lower. However, the WHO states contact times of between 3 and 10 minutes.

[6] Drikas, Mary et al. 2001. "Using coagulation, flocculation, and settling to remove toxic cyanobacteria." Journal American Water Works Association.93 (2), 100-111.
[7] Dugan, Nicholas R., et al. 2001. "Controlling *Cryptosporidium* oocysts using conventional treatment". Journal American Water Works Association 93 (12), 64-76.
[8] USEPA Wastewater Technology Fact Sheet: Ozone Disinfection, 1999. EPA publication EPA 832-F-99-063.

Ozone can also react with dissolved organic carbon in water to produce what is referred to as assimilable organic compounds (AOC). AOC can be utilized by bacteria for growth. Hence, in systems using ozone, it is recommended that ozonation be followed by some means to either remove AOC, or sustain a residual disinfectant. In the LWW case, the ozone recirculation achieves the latter. It should be noted that at the low ozone concentrations we are adding, AOC production may also be minimal. Additionally, the 0.5 μm microfilter is made of activated carbon, which will adsorb many of the AOC precursors.

Summary

Filtration and ozone both contribute significantly to disinfection of drinking water. The current operating conditions of the LWW board would indicate that at least 4 passes are needed at 9 gpm to achieve somewhat effective Ct values. Reducing the flow can help increase Ct values and reduce the number of passes. This calculated result was confirmed by tests at the October 28, 2005 work weekend.

Filtration, by the results stated above, appears to be the workhorse of the disinfection system. A test at the July 2005 work weekend showed that filtered – only water gave a negative pathoscreen result after 48 hours. Filtration followed by ozonation also showed a negative result, with a slightly less cloudy appearance. Tests at the October 28, 2005 weekend showed negative pathoscreen for the filter then ozone treatment sequence.

Accumulation of organisms on the filter and potential exposure of workers to these filters appear to be the biggest concern. Thus, it may be useful to evaluate the microorganism build up on all three of the filters. However, it should be noted that, based on the analysis above, all the filters in all the units installed thus far have had filters exposed to dormant pathogen species, and no incidents of illness due to filter handling have been reported.

Respectfully submitted,

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