

performance. Oocyst removal in the sedimentation basin averaged 0.2 log, and removal by filtration averaged 1.5 log. Under suboptimal coagulation conditions, low sedimentation removals of *Cryptosporidium* were observed regardless of raw water turbidity.

Nieminski and Bellamy (2000) investigated surrogates as indicators of Giardia and *Cryptosporidium* in source water and as measures of treatment plant effectiveness. It involved sampling for microbial pathogens (Giardia, *Cryptosporidium*, and enteric viruses), potential surrogates (bacteria, bacteria spores, bacterial phages, turbidity, particles), and other water quality parameters in the source and finished waters of 23 surface water filtration facilities and one unfiltered system.

While Giardia and *Cryptosporidium* were found in the majority of source water samples, the investigators could not establish a correlation between either occurrence or removal of these protozoa and any of the surrogates tested. This was attributed, in part, to low concentrations of Giardia and *Cryptosporidium* in raw water and high analytical method detection limits. Removal of *Cryptosporidium* and Giardia averaged 2.2 and 2.6 log, respectively, when conservatively estimated using detection limits in filtered water. Aerobic spores were found in 85% of filtered water samples and were considered a measure of general treatment effectiveness. Average reduction of aerobic spores was 2.84 log. Direct filtration plants removed fewer aerobic spores than conventional or softening plants.

McTigue *et al.* (1998) conducted an on-site survey of 100 treatment plants for particle counts, pathogens (*Cryptosporidium* and Giardia), and operational information. The authors also performed pilot scale spiking studies. Median removal of particles greater than 2 mm was 2.8 log, with values ranging from 0.04 to 5.5 log. Removal generally increased with increasing raw water particle concentration. Results were consistent with previously collected data. *Cryptosporidium* and Giardia were found in the majority of raw water sources, but calculation of their log removal was limited by the concentration present. River sources had a higher incidence of pathogen occurrence. Direct filtration plants had higher levels of pathogens in the filtered water than others in the survey.

Nearly all of the filter runs evaluated in the survey exhibited spikes where filtered water particle counts increased, and pilot work showed that pathogens are more likely to be released during

these spike events. *Cryptosporidium* removal in the pilot scale spiking study averaged nearly 4 log, regardless of the influent oocyst concentration. Pilot study results indicated a strong relationship between removal of *Cryptosporidium* and removal of particles (> 3 µm) during runs using optimal coagulation and similar temperatures.

Patania *et al.* (1999) evaluated removal of *Cryptosporidium* at varied raw water and filter effluent turbidity levels using direct filtration. Runs were conducted with both low (2 NTU) and high (10 NTU) raw water turbidity. Targeted filtered water turbidity was either 0.02 or 0.05 NTU. At equivalent filtered water turbidity, *Cryptosporidium* removal was slightly higher when the raw water turbidity was higher. Also, *Cryptosporidium* removal was enhanced by an average of 1.5 log when steady-state filtered water turbidity was 0.02 NTU compared to 0.05 NTU.

Huck *et al.* (2000) evaluated filtration efficiency during optimal and suboptimal coagulation conditions with two pilot scale filtration plants. One plant employed a high coagulation dose for both total organic carbon (TOC) and particle removal, and the second plant used a low dose intended for particle removal only. Under optimal operating conditions, which were selected to achieve filtered water turbidity below 0.1 NTU, median *Cryptosporidium* removal was 5.6 log at the high coagulant dose plant and 3 log at the low dose plant. Under suboptimal coagulation conditions, where the coagulant dose was reduced to achieve filtered water turbidity of 0.2 to 0.3 NTU, median *Cryptosporidium* removals dropped to 3.2 log and 1 log at the high dose and low dose plants, respectively. Oocyst removal also decreased substantially at the end of the filter cycle, although this was not always indicated by an increase in turbidity. Runs conducted with no coagulant resulted in very little *Cryptosporidium* removal.

Emelko *et al.* (2000) investigated *Cryptosporidium* removal during vulnerable filtration periods using a pilot scale direct filtration system. The authors evaluated four different operational conditions: stable, early breakthrough, late breakthrough, and end of run. During stable operation, effluent turbidity was approximately 0.04 NTU and *Cryptosporidium* removal ranged from 4.7 to 5.8 log. In the early breakthrough period, effluent turbidity increased from approximately 0.04 to 0.2 NTU, and *Cryptosporidium* removal decreased significantly, averaging 2.1

log. For the late breakthrough period, where effluent turbidity began at approximately 0.25 NTU and ended at 0.35 NTU, *Cryptosporidium* removal dropped to an average of 1.4 log. Two experiments tested *Cryptosporidium* removal during the end-of-run operation, when effluent turbidities generally start increasing. Turbidity started at about 0.04 NTU for both experiments and ended at 0.06 NTU for the first experiment and 0.13 NTU for the second. Reported *Cryptosporidium* removal ranged from 1.8 to 3.3 log, with an average of 2.5 log for both experiments.

Harrington *et al.* (2001) studied the removal of *Cryptosporidium* and emerging pathogens by filtration, sedimentation, and dissolved air flotation (DAF) using bench scale jar tests and pilot scale conventional treatment trains. In the bench scale experiments, all run at optimized coagulant doses, mean log removal of *Cryptosporidium* was 1.2 by sedimentation and 1.7 by DAF. *Cryptosporidium* removal was similar in all four water sources that were evaluated and was not significantly affected by lower pH or coagulant aid addition. However, removal of *Cryptosporidium* was greater at 22°C than at 5°C, and was observed to be higher with alum coagulant than with either polyaluminum hydroxylchlorosulfate or ferric chloride.

In the pilot scale experiments, mean log removal of *Cryptosporidium* was 1.9 in filtered water with turbidity of 0.2 NTU or less. Removal increased as filtered water turbidity dropped below 0.3 NTU. There was no apparent effect of filtration rate on removal efficiency. In comparing *Cryptosporidium* removal by sand, dual media (anthracite/sand), and trimedia (anthracite/sand/garnet) filters, no difference was observed near neutral pH. However, at pH 5.7, removal increased significantly in the sand filter and it outperformed the other filter media configurations. The authors found no apparent explanation for this behavior. There was no observable effect of a turbidity spike on *Cryptosporidium* removal.

#### Significance of Conventional and Direct Filtration Studies

The performance of treatment plants under current regulations is a significant factor in determining the need for additional treatment. As described in section IV.A, the proposed *Cryptosporidium* treatment requirements associated with LT2ESWTR risk bins for filtered systems are based, in part, on an estimate that conventional plants in compliance with