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Removal of Cryptosporidium parvum Oocysts by Rapid Sand Filtration with Ballasted Flocculation-Filtration and Intermediate Downwashes

A novel and efficient protocol optimising deep-bed filtration of surface water was developed. The innovation lies in ballasted-flocculation filtration and an intermediate downwash. The approach is based on the assumption that kaolin particles with a partial positive charge may adsorb onto the surface of C. parvum oocysts and neutralize their negative charge. Application of this technology enhanced removal of inorganic particles and Cryptosporidium parvum oocysts by approximately 30\% and shortened the ripening stage of the filtration process from 1 h to about 10 min.

Keywords: Ripening, Particle Addition, Hydrodynamic Forces, Kaolin, Deep-bed Filtration

Entfernung von Cryptosporidium parvum-Oozysten mit Hilfe der Schnellsandfiltration: Flockungfiltration mit dotierter partikulärer Grundbelastung und zwischengeschalteten Spülungen im Abstrom

Eine neuartiges Verfahren zur Tiefenfiltration von Oberflächenwasser wird vorgestellt, das mit dem Zusatz von Kaolin bei der Flockungfiltration und zwischengeschalteten Spülsschritten im Abstrom arbeitet. Das Verfahren basiert auf der Annahme, dass die Kaolinpartikel mit ihren positiven Teilbereichen auf der Oberfläche der Cryptosporidium-Oozysten sorbieren und deren negative Oberflächenladung neutralisieren. Durch die Anwendung dieser Technologie wurde die Entfernung von Cryptosporidium parvum-Oozysten um etwa 30\% verbessert und der Zeitraum für die Filterreifung von 1 h auf 10 min verkürzt.

Schlagwörter: Filterreifung, Hydrodynamische Kräfte, Kaolin, Tiefenfiltration, Filterhilfsmittel

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DOI 10.1002/aheh.200200584 © 2005 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim
1 Introduction

The microbiological quality of drinking water has become one of the most important environmental concerns demanding worldwide attention [1, 2]. Among the microbiological contaminants of potable water, the protozoan parasite Cryptosporidium parvum has raised the greatest concern. Considerable circumstantial evidence indicates that C. parvum oocysts may be present in up to 97% of surface water in the U.S. [3]. Found in high concentrations ($10^{10}$ L$^{-1}$) in the feces of infected mammals, these oocysts cause waterborne cryptosporidiosis – an infectious gastrointestinal disease [4] typified by abdominal pain, profuse diarrhea, weight loss, loss of appetite and anorexia. In otherwise healthy individuals, the infection is usually self-limiting and resolves itself within a few weeks [5]. In immunocompromised persons the severity and duration of the illness are often greater and might even be fatal. During the 1993 Milwaukee cryptosporidiosis outbreak, for instance, at least 50 C. parvum-associated deaths were reported among infants, pregnant women, the elderly, and AIDS sufferers [6].

Since drinking water is not usually treated at the household level (by boiling or micromembrane filtration), continuous attenuation of C. parvum oocysts must rely on disinfection at the level of water-treatment plants. The latter treatment is often viewed as a two-stage sequence: removal of particles via sand filtration followed by inactivation of microbes through chemical disinfection, typically chlorination. In view of the inordinate resistance of C. parvum oocysts to chloramines, and even to free chlorine [7, 8], the first stage acquires added importance. As demonstrated earlier [9, 10], rapid sand filtration is capable of meeting the promulgated 99% attenuation level [11] when combined with proper coagulation/flocculation at the optimal operable stage. However, removal rate is periodically compromised during the ripening and breakthrough stages. Absence of a clear distinction where the operable stage begins and ends preceding ripening and following breakthrough enforces the recent trend to supply filtrate of all the stages to the consumers’ tap. Backwashing of sand filters is usually performed on a daily basis; hence the common engineering practice of designing filters deep enough to remain operable between backwashes. Closer attention to the ripening stage of the filtration cycle might therefore be the key to improving the microbial quality of tap water. This observation is strengthened by evidence that up to 90% of the suspended particles [12] in the size range of pathogenic microorganisms may penetrate the filter during the ripening stage.

Techniques proposed for reducing total concentration of suspended particles – irrespective of their origin – include slow start [13], addition of flocculants during backwash [14] and redirection of the ripening filtrate to sewage—commonly referred to as “filter-to-waste”. The latter solution is often substituted by redirection of the filtrate back to the coagulation stage, thus rendering the process both capital- and energy-intensive. Yet, despite implementation of the above-mentioned techniques, the microbiological quality of the filtrate from the ripening stage is far from acceptable for distribution. The worrying presence of C. parvum in treated potable water [15], with sporadic outbreaks of the disease, is still being reported worldwide [16, 17].

This study was conducted using The United States Environmental Protection Agency (U.S. EPA) Test and Evaluation Facility (Cincinnati, OH). It was aimed to improving the removal of microbial parasites and/or to shorten the ripening time. The study was conducted on a suspension of $8 \cdot 10^6$ oocysts L$^{-1}$ in tap water. The study was initiated under the conditions that the oocyst-removal level during the ripening stage was an insufficient 1.7 log. Measurements were taken at a filter depth of 0.8 m. The 1.7-log oocyst removal level increased to more than 3 log when ballasted-flocculation filtration was applied and the ripening sequence was shortened from 1 h to approximately 10 min following “intermediate downwash”. Log removal is defined as log$_{10}$ $C_0/C$, where $C_0$ is the measured influent value (oocysts per liter) and $C$ is the measured effluent value ($C$ oocysts per liter). The minimum detection limit was taken as 50 when no oocysts were detected in the effluent sample.

We designed a pilot-scale filtration system to test a technology for the removal of C. parvum oocysts from drinking water. The technology comprised a standard deep-bed filtration protocol with the following modifications: 1) kaolin alone (for ballasted filtration) or kaolin plus alum (for ballasted flocculation filtration) were added to the feed water before filtration and 2) an intermediate downwash stage was added at the end of the operable stage. Detachment forces were used to deliberately initiate an intensive, rapid, concentrated removal of previously accumulated particles. Intermediate downwash enables operative particle removal levels to be achieved within 10 min, while filtration continues on a “ripe” medium, eliminating ripening of a backwashed medium. A possible explanation of the elementary physicochemical interactions in a grain-particle-flocculant system for the two processes is provided.

2 Materials and method

2.1 Filtration set-up

Figure 1 schematically depicts a pilot-scale filtration system, designed and fabricated specifically for this type of research. The influent was a reverse osmosis (RO) permeate obtained from an on site RO module (model R2D40, Ecodyne Water Treatment Inc., Naperville, IL) used to treat Cincinnati tap water (originally from the Ohio River) that had already under-
gone sand and gravel filtration with alum, granular activated-carbon adsorption, and chlorination. The quality of the RO permeates was consistent throughout the study, with stable values for the pH (5.1–5.3), ionic strength (0.01 M) and conductivity (2.1–2.4 μS cm⁻¹). The influent was mixed with kaolin clay particles in a 1 000-L round polyethylene feed tank by means of a two-blade propeller (model VL3501, Baldor Electric Co., Fort Smith, AR). A centrifugal pump (model AC-3C-MD, March Manufacturing Inc., Glenview, IL) lifted the suspension into a 100-L head tank, from where it flowed by gravity via a 1/4" pipe into a filtration column located 3.6 m below the tank. The flow rate was controlled (and manually adjusted) by a flowmeter (model U-32470-02, Cole-Parmer Instrument Co., Vernon Hills, IL) located at the column outlet. The filter column was constructed from a transparent acrylic water pipe with an inner diameter of 0.17 m and a total height of 2.6 m. Nine sampling ports and nine pressure ports were located in pairs on opposite sides of the column (Fig. 1). Replaceable Teflon tubes were screwed into each monitored port and upon sample collection were dipped isokinetically into 1-L polypropylene particle-free beakers.

### 2.2 Suspension preparation

*C. parvum* stock solution was prepared from Iowa strain oocysts supplied by the University of Arizona obtained from young Holstein bulls. The oocysts were propagated in six-week-old immunocompromised female C57/BL-6 mice [18] following the modified protocol of Yang et al. [19]. In brief, each mouse was inoculated orally with 10⁶ *C. parvum* oocysts in 200 μL of phosphate-buffered saline (PBS) on the eighth day of a dexamethasone-phosphate (0.288 mg L⁻¹) and tetracycline-HCl (0.5 mg L⁻¹) treatment regime, and feces were collected every 36 h for the next two to three weeks. Oocyst extracts from the fecal samples were then purified using an 8.3 mM (1.4 g L⁻¹) CsCl solution, resulting in...
in 99% purity [20]. The purified oocyst samples were suspended in a PBS solution (pH 7.4) containing antibiotics/antimycotics and stored at 4°C until further use. A three-week to one-month-old sample with a titer of $8 \times 10^6$ L$^{-1}$ oocysts was injected into the inflow 1 m above the filter column.

Weighed kaolin clay particles (Sigma-Aldrich Inc., St. Louis, MO) were dispersed in 1 L of the RO permeate by mixing for 3 min in a kitchen blender (Betty Crocker 8 Speed Blender) at high speed. The suspension was poured into the feed tank at least 2 h prior to the start of the experiment. Blended) at high speed. The suspension was poured into the feed tank at least 2 h prior to the start of the experiment. The pertinent physical characteristics of suspension-forming kaolin particles and C. parvum oocysts are presented in Table 1.

### 2.3 Filtration protocol

Filtration was performed in contact (in-line) down-flow mode at constant rates of 5 m$^3$ m$^{-2}$ h$^{-1}$, 10 m$^3$ m$^{-2}$ h$^{-1}$ and 20 m$^3$ m$^{-2}$ h$^{-1}$, often expressed as an approach velocity $u = Q/A$, where $Q$ (unit: m$^3$ h$^{-1}$) is incoming flux and $A$ is the cross-section area of the filter (0.023 m$^2$ in the current study). After each run, the filter was backwashed for 1 min by air at 200 kN m$^{-2}$ pressure, followed by a 10 min backflow of Cincinnati tap water at 1.1 L s$^{-1}$.

The filtration column was packed to a depth of 1.6 m with 1.05-mm effective-size (ES) sand having a uniformity coefficient (UC) of 1.55 (#5 Silica Torpedo Sand, Parry Company, Richmond Dale, OH). Before the start of the experiment, the sand was washed with deionized water, soaked in 0.05 M HCl solution for 24 h, dried at 110°C and washed again with deionized water. The initial porosity of the filter bed, determined volumetrically, was $\varepsilon_0 = 0.44$.

A three-week to one-month-old sample with a titer of $8 \times 10^6$ L$^{-1}$ oocysts was injected into the inflow 2 m above the filter bed. The monitored ports were located at depths of −2 cm, 10 cm, 40 cm, and 80 cm inside the filter bed (Fig. 1). The 1.6-m depth port was monitored for discharge control purposes. The total depth of 1.6 m proved sufficient to provide no less than 3-log attenuation of the initial C. parvum concentration.

The optimal dose of alum coagulant/flocculent [Al$_2$(SO$_4$)$_3$·18H$_2$O, Sigma-Aldrich] was established as follows. The initial suspension of kaolin and the oocysts with various dosages of added alum was poured into 1-L beakers and tested using the following protocol: (i) rapid mix in a conventional multiple stirrer jar (Phipps and Bird 7790-402, Richmond, VA) at 100 rpm for 1 min; (ii) slow mix at 30 rpm for 20 min; or (iii) quiescent settling for 30 min. Samples collected by slow decantation from the upper part of the test jars are analysed for turbidity and oocyst concentration.

### 2.4 Sample analysis

After sampling, the beakers were capped and stored in a Biohazard refrigerator until analysis, which was performed within 72 h of sample collection, by filtration/immunomagnetic separation (IMS)/immunofluorescence assay (IFA) microscopy [21], as follows. The sample was concentrated to a volume of 0.1 mL by centrifugation for 10 min at 3 000 $\times$ g using a model PR-700M centrifuge (International Equipment Company, Needham Heights, MA), then for 15 min at 20 000 $\times$ g using an Eppendorf 5403 centrifuge (Brinkmann Instruments, Westbury, NY). Samples were stained with a direct fluorescent monoclonal antibody containing 1 part of Crypt-a-Glo (Waterborne Inc., New Orleans, LA) in 2 parts of goat serum (Sigma Co., St. Louis, MO). C. parvum oocysts were counted with a Neubauer hemacytometer under a UV microscope at 40x magnification (Carl Zeiss Microimaging, Thornwood, NY).

Samples for turbidity analysis were collected into 20-mL sampling vials and analysed immediately in a model 2100P turbidimeter (Hach Co., Loveland, CO). To avoid head-loss surges, the monitored sampling ports were kept constantly open to permit rapid dripping.

Zeta potential was measured with a Malvern Zetasizer (Malvern Instruments Ltd., Malvern, Worcestershire, U.K.).

### Table 1: Physical characteristics of suspension-forming substances.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Size</th>
<th>Density</th>
<th>$\zeta$-potential in influent</th>
<th>$\zeta$-potential in influent with addition of 20 mg L$^{-1}$ alum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaolin</td>
<td>0.8 ± 0.3</td>
<td>2.6</td>
<td>−10.3</td>
<td>−3.3</td>
</tr>
<tr>
<td>C. parvum oocyst</td>
<td>4.8 ± 0.6</td>
<td>1.045</td>
<td>−16.0</td>
<td>−1.3</td>
</tr>
</tbody>
</table>

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Samples were injected into 1.5-mL quartz capillary electrophoresis measurement cells with 10-mL disposable syringes.

3 Results and discussion

3.1 Kaolin influences the removal of *C. parvum* oocysts

The results of experiments performed at a 10 m h\(^{-1}\) approach velocity with no chemical destabilization are given in Figure 2. Filtration efficacy was evaluated by plotting the oocyst removal ratio \([1 - (C/C_0)]\) as a function of time from the beginning of the filter run. The samples for analysis were collected at a filter depth of 0.4 m in three consecutive experiments performed without alum at constant influent concentrations of 10 mg L\(^{-1}\) and 20 mg L\(^{-1}\) of kaolin. The experiments were allowed to run for 1 h, which is the typical ripening period for all three approach velocities under current experimental conditions [22]. That time period allowed a constant supply of *C. parvum* oocysts.

A similar set of experiments was performed with the addition of 20 mg L\(^{-1}\) of alum (Fig. 3). As expected, adding alum increased filtration efficiency. In experiments performed without kaolin, *C. parvum* oocyst removal reached a level 0.85 log and remained stable throughout the ripening stage. Addition of kaolin (10 mg L\(^{-1}\) or 20 mg L\(^{-1}\)) resulted in 2-log oocyst removal after a 1-h filter run. Effectiveness of alum addition was depicted also during jar tests. Sedimentation of up to 75% of oocysts was achieved with 40 mg L\(^{-1}\) of alum [22]. That relatively high concentration of added alum was considered to trigger mechanism of “sweep coagulation” that incorporates adsorption of the particles onto the surface of Al(OH)\(_3\) precipitates regardless of their charge. Lower concentration of 20 mg L\(^{-1}\) was considered as promoting the neutralization of negative charge of the influent particles by positive aluminium hydroxide species Al(OH)\(^{2+}\), Al(OH)\(_3^+\), and Al\(_{13}\)O\(_{45}\)(OH)\(_{24}\)\(^{7+}\) [23]. The opposite scenario of “charge neutralization” suggests shielding the negatively charged sites on the molecular rim in the Stern layer of the electrical double layer.

Graphs of the turbidity removal ratio vs. run time with the addition of 10 mg L\(^{-1}\) kaolin, with or without alum (Fig. 4) — show typical curves of initial deterioration in filtrate quality followed by a gradual increase in removal ratios as the filter run progresses. Two surprising tendencies — not intuitively obvious — concerning oocyst removal were discovered. First, the oocyst residual ratio remained constant throughout the ripening stage. Second, adding non-destabilized kaolin particles to raw water containing *C. parvum* resulted in approximately 60...75% oocyst removal, compared to almost zero removal from suspension not supplemented with kaolin. The improved removal ratios obtained by adding alum may be attributed to lowering of the surface charge of both the mineral particles and the kaolin (Table 1) without changing the observed tendencies, i.e., the improvement with kaolin is maintained.

If we consider kaolin particle-oocyst-sand grain interactions from an electrostatic perspective, we may assume that when neither kaolin nor alum is present in the suspension, strong repulsive forces between negatively charged sand grains...
and negatively charged *C. parvum* oocysts (Table 1) cause uninterrupted transport of the latter through the interstitial channels of the filter. Added kaolin particles interact with the oocysts in the suspension, causing partial neutralization of the oocysts' negative charges. The internal bridging position of kaolin particles [24] may be due to their layered structure and the partial positive charges on their edges. The effect depends linearly on the initial kaolin concentration and may be as significant as adding alum alone. Simultaneous addition of alum and kaolin results in aggregation of multicomponent alum-kaolin-oocyst flocs with improved settling abilities [25].

### 3.2 Ballasted-flocculation filtration

The proposed view suggests that addition of a limited quantity of destabilized kaolin particles to the initial suspension will shorten the ripening sequence and improve initial filtrate quality. The idea is to add large-surface-area particles to maintain the colloidal concentration at a level where rapid coagulation and flocculation occur (coagulation rates in dilute colloidal suspensions may be extremely slow due to an inadequate number of interparticle contacts). An excessive dose of coagulant would not be helpful, since it might cause restabilization of the colloids. Blank experiments showed that adding kaolin not flocculated with alum resulted in increased filtrate turbidity. Moreover, too high a concentration of kaolin particles clogged the filter and led to early filter breakthrough. Conversely, too low an amount of kaolin had no effect on the filtration process.

Figure 5 depicts comparative filtration experiments performed with and without added ballast. The effect of aggregating particles vs. run time on turbidity (Figs. 5A and 5C) and oocyst count (Figs. 5B and 5D) was monitored. Experiments were carried out using 5 mg L$^{-1}$ of kaolin added over 30 min at an approach velocity of 10 m h$^{-1}$ (Fig. 5A and 5B) and 2.5 mg L$^{-1}$ of kaolin over 10 min at 20 m h$^{-1}$ (Fig. 5C and 5D). Samples were collected from the port located at a depth of 0.4 m. Although the general form of the filtration curves remained similar, addition of kaolin particles caused a systematically positive effect on removal efficiency. Three hours after the filtration cycle began, the residual turbidity for the added-ballast curve was 0.6 nephelometric turbidity units (NTU) (Fig. 5A) vs. 1.1 NTU for the control filtration curve.

The obtained data were analysed by theoretical approximations using an idealized advection-accumulation equation with irreversible attachment kinetics, simplified to neglect hydrodynamic dispersion:

$$\frac{\partial}{\partial t}((\varepsilon_0 - \gamma_p)C_t) + K_r C_t + C_t + u + \frac{\partial C_t}{\partial Z} = 0$$

where

- $C_t$: pollutant concentration in the liquid phase;
- $K_r$: ripening attachment rate coefficient;
- $t$: time;
- $u$: approach velocity;
- $Z$: longitudinal coordinate (oriented in the direction of mean flow);
- $\varepsilon_0$: porosity of a clean filter bed;
- $\gamma_p$: specific deposit (the total mass of deposited contaminants per unit volume of the filter);
- $\rho_d$: physical deposit layer density.

Values of $K_r$ were varied to attain the closest possible approximation of experimental data by theoretical curves using the best-fit value method. Obtained values of $K_r$ were compared to the filter coefficient $\lambda$ [26, 27]:

$$\lambda = \frac{\ln(C_t/C_0)}{L}$$

where

- $L$: filter depth.

The validity of the accumulation kinetics approximation was verified by counting the oocysts collected from samples at filter depths of 10 cm, 40 cm and 80 cm (Fig. 6).

A plot of *C. parvum* oocyst removal vs. filter depth exhibited a clearly logarithmic behavior. At a depth of 10 cm, removal efficiency was 0.5 log at the beginning of the run and grew to 1.6 log after 2 h. At 40 cm, efficiency was found to rise from 2.1 to 3.9-log removal. At 80 cm, removal increased...
Rapid Sand Filtration of *C. parvum* Oocysts

from 3 to 4 log during the first hour, after which tracking became impossible due to minimum detection limitations.

Thus, comparing the approximated filtration efficiency on $\lambda$ and $K_r$, a consistent enhancement of 10...60% in filtration efficiency was achieved by adding kaolin (Table 2). The effect was even more pronounced for the beginning of the run, where the residual oocysts concentration varied between 56 oocyst mL$^{-1}$ and 20 oocyst mL$^{-1}$ (Fig. 5B).

The above-described experiments show that ballast systematically improved the filtration curves. True, the duration of the filtration stages varied in each case, but in all of the experiments the residual concentration was lower when additional flocculated particles were present. We can therefore conclude that addition of such aggregating seeds (in this case kaolin particles) shortens the ripening period and improves filter efficiency.

**3.3 Creating efficient “intermediate downwash” using controlled hydrodynamic forces**

The fate of suspended particles in a sand filter is determined by transport and attachment/detachment phenomena [25, 28]. While the particles may be brought into close proximity to the sand grain surfaces, their attachment to the sand grains is balanced by electrostatic van der Waals/repulsion interactions and detachment forces. The hydrodynamic nature of the detachment forces was discussed in our previous communication on a new batch reactor [24]. Particle detachment becomes significant as the filter run progresses and particles accumulate inside the pores of the medium. The negative effect of detachment forces on filtrate quality is well known, and it is generally recommended [29] that possible artificial changes in head loss (pressure drop across filters)
Table 2: Values of filtration coefficients $K_r$ and $\lambda_0$ obtained from the study. $L = 0.4$ m, sand $ES = 1.05$ mm; C. parvum oocyst $= 8 \cdot 10^6$ $L^{-1}$; kaolin $= 10$ mg $L^{-1}$; alum $= 20$ mg $L^{-1}$. Values in parentheses are for the curves when no kaolin was added.

<table>
<thead>
<tr>
<th>Addition of kaolin particles</th>
<th>$u$ m h$^{-1}$</th>
<th>Turbidity removal $K_r$ m$^{-1}$</th>
<th>$\lambda_0$ m$^{-1}$</th>
<th>Oocyst removal $K_r$ m$^{-1}$</th>
<th>$\lambda_0$ m$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 mg L$^{-1}$ over 30 min</td>
<td>10</td>
<td>3.6 (3.2)</td>
<td>7.7 (4.8)</td>
<td>20.0 (12.0)</td>
<td>18.0 (16.1)</td>
</tr>
<tr>
<td>2.5 mg L$^{-1}$ over 10 min</td>
<td>20</td>
<td>4.4 (3.2)</td>
<td>5.8 (4.8)</td>
<td>10.8 (9.6)</td>
<td>16.9 (15.5)</td>
</tr>
</tbody>
</table>

be minimized. Thus, if smooth mechanical adjustments [30] can cause significant particle detachment, then, presumably, a thorough shake-up of the filter bed by intentional head-loss perturbation will re-introduce accumulated particles back into the flow.

With an “intermediate downwash”, the idea is to thoroughly shake-up the filter bed hydrodynamically to resuspend the particles that are loosely attached to the filter grains. It was speculated that such a downwash would serve to flush the particles not tightly bonded to the grains of the medium (first-layer particles) out of the column. The major advantage of downwashing is the possibility of performing a wash that is not necessarily followed by a ripening period. The economic benefits include saving the cost of an extra backwash pump and pipes and lower operational expenses for energy and chemicals. The negative aspect is the idea of purging the filter medium in the direction of the main flow and risking pathogens penetrating closer to the filter exit, along with the considerable risk of further detachment during the run.

An “intermediate downwash” was performed by suspending the flow through the filter during the operable stage. The pause was deliberately initiated by quickly shutting off the effluent valve manually for a 5-min period. Experiments performed at 5 m h$^{-1}$ (Fig. 7A) and 10 m h$^{-1}$ (Fig. 7B) were tracked in terms of head loss and residual turbidity at 0.4-m filter depth and plotted against run time in hours.

Rapidly and fully re-opening the valve created a massive downwash to the drain in the short time interval of 5...10 min. The turbidity of the wash slurries was as follows: > 2 000 NTU (detection limit) for up to 4 min, then approximately 700 NTU for a further 2 min. Two to four minutes more and the residual turbidity dropped further to < 1 NTU and remained stable until the next wash. Similar levels of residual turbidity were achieved previously [31] after a ripening period of at least 1 h. The wash was repeated up to
Since no backwash was required, the approach was termed "continuation of the filter run after each consecutive wash.

five times during each run, and followed by an undisturbed continuation of the filter run after each consecutive wash. Since no backwash was required, the approach was termed "intermediate downwash".

4 Conclusions

This study demonstrates that addition of ballast particles consistently reduces the frequency and duration of the ripening sequence based on the assumption that partially positive charged kaolin particles may adsorb onto the surface of C. parvum oocysts and neutralize their negative charge. The proposed view was successfully developed into a ballasted-flocculation filtration technique used to enhance removal of inorganic particles and C. parvum oocysts.

Results from pilot scale experiments, provided in the current communication, clearly show the advantages of the proposed methods. However, the practical consideration disadvantages, and control of these methods should be examined on full-scale filters prior to drawing any final conclusions. If the described methods show similar positive trends under a variety of testing conditions, the proposed filter-run optimization could positively affect removal of pathogenic microorganisms during the ripening stage of rapid sand filtration.

Acknowledgements

This study was supported by the U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Water Supply and Water Resources Division through contract No. 68-C-99-211, Work Assignment No. 1-03, with IT Corporation. The authors thank James H. Owens of U.S. EPA for providing purified C. parvum oocysts and Lee Heckman from IT Corporation for training in C. parvum sampling and analysis. The views expressed in this paper are those of the authors and do not necessarily reflect the views of the U.S. EPA.

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[Received: 27 June 2002; resubmitted: 2 March 2005; accepted: 11 July 2005]