Concentrate Disposal Via Injection Wells — Permitting and Design Considerations

Sean Skehan and Peter J. Kwiatkowski

Updates to the Safe Drinking Water Act — including more restrictive drinking water standards for disinfection by-products — have led many utilities to consider upgrading water treatment plants to membrane processes. A result is the need to dispose of membrane concentrate in an environmentally acceptable manner. Limited success has been achieved with surface discharge of this brackish-to-saline concentrate into surface water bodies near the coast. However, many utilities do not have this option because of their geographic location inland or their proximity to environmentally sensitive surface water bodies, such as the Indian River Lagoon.

Injection well systems are an effective means of concentrate disposal. Although deep injection wells are far from an easy permitting experience, they are frequently the most environmentally friendly means of concentrate disposal.

The permitting process itself can lead to selection of injection well systems, given the limited number of alternatives. Permitting considerations focus on literature identification of adequate geologic confining units to prevent upward migration of effluent from the injection zone.

Design considerations focus on the tubing and packer assembly installed inside the final cemented casing of the injection well. Other factors include compatibility of the concentrate with the tubing material (corrosion potential), anticipated permeate and concentrate flows, tubing diameter selection in the retrofit of existing deep injection wells, and annular monitoring systems for leak detection.

CASE STUDY 1: Retrofit of an Existing Deep Injection Well for Concentrate Disposal from a Low-TDS Membrane-Softening Plant

This project involves concentrate disposal from a municipal, membrane-softening WTP in Palm Beach County. The most cost-effective, environmentally friendly means of concentrate disposal was deemed to be the retrofit of an existing deep injection well previously used to dispose of secondary effluent from a municipal wastewater treatment plant.

The existing injection well had a 20-inch-diameter carbon-steel injection casing cemented from land surface to a depth of approximately 2,800 feet.

The major task of the retrofit consisted of installing a liner (tubing) inside the existing injection well and a permanent, mechanically set packer – providing for a fluid-filled annulus to monitor mechanical integrity of the tubing.

Permitting Issues

The DEP Underground Injection Control (UIC) group in West Palm Beach has regulatory authority over injection wells in southeast Florida. Retrofit of an existing deep injection well for concentrate disposal was a first in this area. Therefore, a relatively stringent interpretation of the UIC rules was enforced in this case. That is, a new UIC well construction permit was required.

Although the deep injection well had already demonstrated its suitability for injection with secondary effluent, this more elaborate process resulted in longer project duration. In particular, area of reviews, demonstration of confinement of the injection zone, compatibility of the concentrate with the aquifer matrix, an injection test, and the public comment process were required again.

Sean Skehan, P.G., is with CH2M HILL, Deerfield Beach. Peter J. Kwiatkowski, P.G., is with the South Florida Water Management District, West Palm Beach.

Design Considerations

The source water is from the surficial aquifer system in South Florida. The water is moderately hard, with a relatively low TDS content of approximately 150 mg/L. The relatively low TDS concentration of the source water allayed corrosion concerns, allowing a more cost-effective liner material (carbon steel) to be used. A 16-inch-outside-diameter tubing (1/2-inch wall thickness) with threaded couplings and O-rings was the chosen design. The 16-inch diameter was chosen to fit inside the existing 20-inch casing and comply with the 8-fps maximum injection velocity (6.34 MGD) criteria allowed at the time by DEP. A permanent, mechanical packer was set 20 feet above the base of the injection casing. A polished bore receptacle provided the mechanical seal between the 16-inch tubing and the packer. A corrosion-inhibitor fluid (Cronox 9862) was used between the tubing and casing, but is considered precautionary because the tubing and casing are constructed of the same carbon steel.

The annulus between the tubing and casing was sealed at the wellhead, and connected to an annulus pressure tank. The tank was filled with corrosion-inhibitor fluid, pressurized with an air compressor, and operated at a pressure greater than the maximum operating pressure of the deep injection well. In this way, if a leak in the tubing occurs, the fluid will drain from the tank signaling an alarm in the control room.

Project Approach

The tubing-and-packer retrofit consisted of several components. The existing 20-inch-diameter injection casing was inspected via borehole video survey to ensure that a liner could be installed. In addition, a dummy (blank, 20-foot section of casing with the same diameter as the proposed liner) was run on drill pipe into the well. A strain gauge at the wellhead was used to measure relative resistance as the dummy was lowered into the final casing. This provided some assurance that the full string of 16-inch tubing could be successfully run inside the existing 20-inch casing. A pre-tubing casing pressure test was also conducted to demonstrate internal mechanical integrity. If the future annulus pressure test failed, one could isolate the cause to the failure to the tubing itself. Removal and reinstallation of the tubing could then be attempted.

The packer was lowered and set on drill pipe to the desired depth. A steel ball was dropped inside the drill pipe, forcing a shear pin to mechanically set the packer. Tubing installation was accomplished with power tongs to document the required, manufacturer-recommended torque for each tubing joint to ensure an adequate seal.

Discussion

Since this project was completed, a more simplified permitting process has been allowed — a modification of an existing UIC well operating permit — that resulted in a more streamlined, less arduous permitting process for an existing well that is already in compliance with UIC regulations. In addition, a $1,000 permit fee versus a $10,000 fee for new construction is more reasonable given the project intent.

DEP now allows injection wells to operate at 10 fps and, in emergency conditions, 12 fps. In theory, this would allow larger diameter tubing to be installed. However, a delicate balance must be maintained between injection capacity and tubing diameter that will fit inside an existing casing for retrofit applications.

The tubing-and-packer design provides the regulatory-required continuous monitoring of the annulus between the tubing and cemented casing to evaluate mechanical integrity. The relatively low TDS concentrations of the concentrate in this case study (compared to brackish, e.g., Floridan aquifer, or saltwater sources) and performance of the system to date confirms the viability of carbon steel casing as a liner material.

Case Study 2: Evaluation and Design of a Concentrate Disposal Well for a Reverse Osmosis Facility at the Fort Pierce Utilities Authority

When work was first started on the preliminary design for the Fort Pierce Utilities Authority RO WTP, a major goal was to identify ways in which the overall cost of the project could be reduced. Because of the significance of reject disposal costs, the options considered most reasonable were discharge to a canal leading to the Intracoastal Waterway and disposal via a deep injection well. Evaluation of both disposal methods indicated that use of injection wells over the long term would be the most cost effective means of disposal due to the significant uncertainty related to water quality and surface discharge. Subsequent consideration was given to design of a Class V injection well instead of a Class I injection well. The anticipated advantages associated with a Class V well compared with a Class I well were as follows:

- Depth of the well is approximately 1,500 feet, compared to approximately 3,200 feet for a Class I injection well.
- Cost of the Class V injection well system is estimated to be $1.2 million versus an estimated cost for a Class I well system of $2.5 million.
- Time of construction for a Class V well is estimated to be about 60 days. A Class I well is estimated to take about 180 days to construct.

During a design kick-off meeting with the Fort Pierce Utilities Authority team, options for reject disposal and criteria were discussed extensively. As a result, a decision was made to make a more complete evaluation of the disposal options prior to starting the design. It was agreed that the disposal design would be for a minimum of 2 MGD and that the year 2010 would be used for projections on water demand. Additional action items that were identified included:

- A cost benefit analysis to be conducted on the recovery percentages from the RO process versus the class of disposal well to pursue.
- An evaluation of an intermediate injection interval.
- A determination of the final casing diameter and maximum capacity of reject.

Design Considerations

Because no other systems (known to the authors) are currently permitted to use a Class V injection well for concentrate disposal, it was recognized that there was a certain level of uncertainty in pursuing this course. In order to use a Class V well, the quality of the water being injected must meet the primary and secondary drinking water standards or not exceed the water quality of the receiving zone. Data from a pilot study conducted several years earlier using water from an existing Floridan aquifer well indicated that the membranes could be operated at a recovery rate between 85 and 90%. At these recovery rates, fluoride and radionuclides were the only parameters in the concentrate that exceeded both the drinking water standards and expected native water concentrations of the target receiving zone. For fluoride, it was thought that an exemption would only be needed for the secondary standard because at 70% recovery, the concentration (estimated to be 2.86 mg/L) would be less than the primary standard of 4 mg/L. A water quality criteria exemption was considered to be fairly routine, requiring only DEP approval for the secondary standard.

However, projected radionuclides concentrate quality was on the border of meeting the drinking water standards. Recent samples collected from new Floridan aquifer wells were found to have variable results. In discussions with DEP, it was pointed out that the variability of radionuclides data from each well would have to be clearly understood to allow permitting.

Furthermore, because of the variability of the water quality samples, it is not certain that the 70% recovery rate could be maintained. If there were any deterioration in raw water quality in the future, a further reduction in the recovery rate might be required in order to continue use of the Class V well.

Another complicating factor in this scenario is the water quality of the receiving zone for a Class V well. Currently, there are no other wells in the vicinity that are completed to the expected 1,500-foot depth of the Class V well. Therefore, the expected water quality, which the concentrate must meet, is an assumption. If a Class V permit were granted and testing of the water quality in that zone determined that the water quality was higher than expected, additional reduction in the recovery rate could be required, or additional drilling to find a more acceptable receiving zone might be necessary.

A final complicating factor in this scenario was the proximity of the Floridan aquifer production wells to the injection well location. The vertical separation of the production wells and the Class V injection well would have been less than 400 feet. Additionally, to assure compliance with the drinking water standards, the membranes would have to be operated at rates as low as 70% recovery. This lower recovery rate would require a larger amount of raw water supply, and this additional raw water supply would have the following impacts on the project:

- The total raw water supply, assuming the original 85% recovery with a 25% blend ratio, would be 6.04 MGD.
- At the lower recovery rate of 70%, but still using a 25% blend ratio, the raw water supply must be increased to 7.05 MGD.
- With the additional 1 MGD of raw water supply required, the total number of raw water wells would increase from 9 wells at the 85% recovery rate to 11 wells at the 70% recovery rate.
- Based on a well spacing of 1,000 feet, an additional 2,000 feet of raw water pipeline would be required.
- The additional raw water flow would also have an impact on the pipe sizing from the well field and through the membrane plant.
- The placement of the Class V well would have to be closely evaluated with the production wells in mind, and it is likely the well would have to be placed off site. As a result, a location would have to be selected and a pipe route determined; all additional costs.

Injection Well Capacity Needs

Size of the injection well was given further consideration with respect to the 2-MGD minimum flow and designing the well for the year 2010. By designing for a Class I disposal well, the RO recovery design will be higher (80-85%) and the amount of reject (1.0 to .7 MGD) will be significantly less than at a recovery rate of 70% (1.7 MGD of reject). Assuming the RO process will be designed in the 80–85% recovery range, a 10-inch Class I disposal well will provide adequate disposal capacity (3.5 MGD) for a 12-MGD RO facility.

Based on the factors presented above, it was our recommendation to abandon the Class V scenario and proceed based on using a Class I industrial injection well for concentrate disposal.

Project Approach

Given the decision to proceed with the design of Class I industrial well, the well was designed with multiple steel casings with a 10-inch inside-diameter fiberglass reinforced plastic liner. The design also included the use of a stainless steel mechanical packer set near the bottom of the final casing and a polished bore receptacle to provide the seal between the final casing and liner string. Similar to Case Study No. 1 above, the annulus between the liner and casing will be sealed at the wellhead, and connected to an annulus pressure tank. The tank will be filled with corrosion-inhibitor fluid, pressurized with an air compressor, and operated at a pressure greater than the maximum operating pressure of the injection well as a method of leak detection.

Case Study No. 3: Disposal of RO Concentrate at Florida Keys Aqueduct Authority Marathon/Stock Island RO Facilities

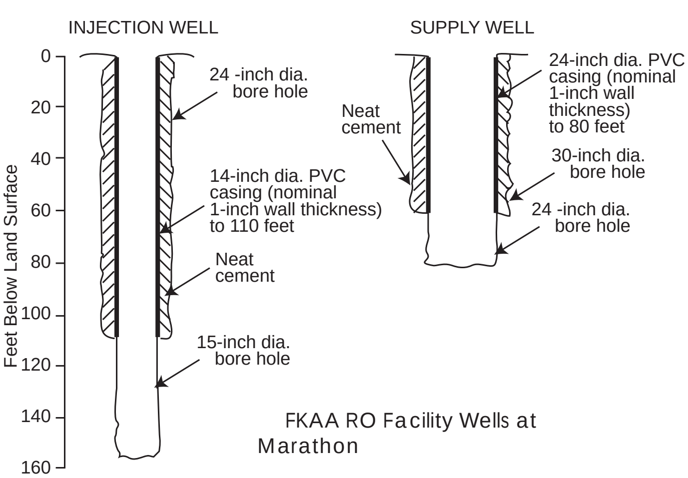
Potable water throughout the Florida Keys is provided through a 120-mile transmission line from the FKAA wellfield in Florida City to Key West. To provide emergency water supply, RO facilities are currently being constructed on Marathon (Middle Keys) and Stock Island (Lower Keys).

To provide 0.9 MGD of finished water at the Marathon location, approximately 3.1 MGD of raw water will be needed. The feed water will originate from a shallow well constructed to approximately 60 feet. To dispose of concentrate from the facility, a shallow injection well was constructed to approximately 150 feet. As part of the construction process, a hydrogeologic/hydraulic study was conducted to evaluate conditions in the shallow aquifer to determine if both supply and disposal were possible. Following the successful construction and testing at the Marathon location, a similar procedure was implemented at the Stock Island site. The primary focus of this discussion will be the Marathon facility.

Permitting Issues

Initially, a surface water discharge was given consideration for concentrate disposal at both locations because of the proximity of canals and ocean-access channels. Although a surface water discharge is theoretically permittable under the existing rules and regulations, it was considered to be a formidable and costly review process of approximately two years, with a low prospect for a successful resolution. As a result, a recommendation was made to the FKAA to proceed with a plan to use Class V injection wells at both facilities. Permitting for both facilities took place through the Fort Myers and Marathon DEP offices and SFWMD.

Placement of the supply and injection wells was based on SFWMD and DEP regulatory requirements that state public supply wells are to be located no closer than 200 feet from any sanitary hazard (such as a septic system). As a result, the supply well was placed approximately 210 feet away from the closest septic system. The injection well was placed approximately 455 feet away from the supply well, constructed to meet Class V injection well criteria, and testing conducted as requested by DEP. The purpose of the testing was to ascertain if hydraulic communication existed between the production zones of the supply and the injection wells.



FKAA RO Facility Wells at Marathon

Design Considerations

Given the size of the site, the production and injection wells were placed at the maximum possible horizontal distance apart, 455 feet. Vertically, the wells were separated by an interval that is 31 feet in thickness. Water throughout the surficial aquifer is consistent and similar to ocean water in quality. Based on the water quality and the depth of construction for the wells, large diameter PVC pipe was selected as the casing material.

Construction

Using direct-air drilling, construction of the production well took place in two stages; the first to a depth of 60 feet bls using a 30-inch-diameter bit, and the second to a depth of 79 feet using a 24-inch-diameter bit. The well was drilled in stages to facilitate installation and cementing of a 24-inch-outside-diameter PVC casing (0.978-inch wall thickness). Following installation of the casing to a depth of 60 feet, the casing was cemented in place in two stages using neat cement.

Drilling of the injection well took place, as with the supply well, in two stages; the first to a depth of 110 feet using a 24-inch-diameter bit and the second to a depth of 155 feet using a 15-inch-diameter bit. Cementing of the 14-inch-diameter PVC casing (0.978-inch wall thickness) was completed from 110 feet to land surface in two stages using neat cement.

The lithology encountered while drilling each well was consistent and characteristic of the Key Largo Limestone. The samples from land surface to 150 feet were described as hard, coralline limestone with varying quantities of shell, sand, and recrystallized limestone.

Hydraulic Testing

An aquifer test was conducted on the injection well to evaluate if communication could be demonstrated between the supply well, and to calculate a specific capacity. The injection well was pumped at approximately 2,500 gpm for 6 hours, while measuring water levels in both the injection and the supply wells. At the injection well, a maximum drawdown of 1.4 feet (corrected for tidal influences) was observed, with a calculated specific capacity of 1,785 gpm/foot of drawdown. An analysis of the drawdown data indicated no measurable effect on water levels at the supply well for the duration of the test.

Conclusions

Injection wells are a cost-effective, environmentally sound mechanism for concentrate disposal from membrane WTPs. Although, injection well permitting is not a task to be taken lightly, other disposal alternatives present more permitting challenges. ■

Cryptosporidium Removal from a Highly Colored Florida Surface Water: A Pilot Study

Matt Alvarez, Bill Bellamy, Joan B. Rose, Chuck J. Gibson, and Pat Fleming

The city of Melbourne uses Lake Washington as its source for potable water and operates a 20-MGD conventional surface water treatment plant. The city conducted a pilot study in August 1998 to identify improvements for a facility upgrade and potential expansion.

Lake Washington's raw water TOC exceeds 30 mg/L, and color can exceed 300 color units. The highly variable organics in the lake can change up to 50% in one storm event. Also, the raw water particles and turbidity can double after a storm. Such variations often occur within 30 minutes.

The city evaluated high-rate treatment processes that could be used to quickly respond to drastic variations in water quality. Loading rates for a typical conventional surface water treatment plant can be 1 gpm/sq.ft. or less. The processes tested in our pilot program, including microsand (ballasted) clarification, solids blanket clarification, and dissolved air flotation, had loading rates between 3 and 30 gpm/sq.ft. Retention times in these units can be as low as 15 minutes. The pilot units tested ranged from 25 to 300 gpm.

Both settled water quality and filtered water quality were evaluated. The settled water from each pilot unit was filtered through conventional dual media filters. Filtration rates between 4 and 6 gpm/ft^2 were evaluated as well. The high rate clarifiers were compared to conventional clarification by assessing the performance of the existing water treatment plant in the same manner as the pilot units.

Treatment effectiveness was evaluated by monitoring turbidity and particle counts after clarification and filtration. Turbidity measurements did not demonstrate significant differences among the treatment alternatives, while particle counts demonstrated significant differences. Treatment efficacy was further assessed by spiking with formalized *Cryptosporidium* oocysts and evaluating removal efficiencies.

Matt Alvarez and Bill Bellamy are with CH2M Hill, Orlando and Denver, respectively. Joan B. Rose and Chuck J. Gibson are with the University of South Florida. Pat Fleming is with the city of Melbourne.

Purpose and Goals

Based on the need to upgrade and replace some of the treatment plant facilities, the Lake Washington pilot study was conducted to determine the suitability of high-rate processes for treatment of Lake Washington waters, to assess the performance benefits of the newer high rate clarification technologies being tested, and to collect design criteria and data for the technologies being tested.

More specifically, the pilot program was designed to simultaneously evaluate the performance of three high-rate water treatment processes, including dissolved air flotation (DAF) provided by Leopold, Inc., a solids blanket clarifier (Super-P) provided by Infilco, Inc., and a ballasted clarifier (Actiflo) provided by Kruger, Inc.

DAF utilizes microbubbles to float coagulated particles (floc) out of the water. The solids blanket clarifier flocculates and then captures the floc in a suspended blanket of solids. The solids are captured hydraulically by passing the treated water upward through the solids blanket. The ballasted clarifier attaches the floc to small sand particles to make them settle faster during clarification. Settling rates are upwards of 30 gpm/ft^2 for this process.

Evaluating Clarifier Performance

During the testing, the performance of the three high-rate clarification processes and the existing Dorr-Oliver unit were evaluated by monitoring the clarified water quality. The parameters monitored in the evaluation included UV-254, TOC, total particles, and turbidity. All of the processes were operated side by side under the same treatment conditions.

In addition, each of the high rate technologies was evaluated to determine its oocyst removal capabilities. Each process was challenged three times with formalized *Cryptosporidium* oocysts. During the spiking, both online turbidity and particle measurements were made. The coagulation conditions were monitored during the spiking period and kept constant over the three processes to assess the effect of coagulation in oocyst removal for each type of clarification process. Ferric sulfate was used as the coagulant at a pH of approximately 4.0.

In monitoring clarifier performance throughout the study, the particle count ranges were 2 to 5, 5 to 10, 10 to 15, and > 15 microns. These particle ranges effectively cover the sizes of *Cryptosporidium* and *Giardia*.

Methodology

Each process was challenged three times with formalized *Cryptosporidium* oocysts. The seeded challenges consisted of 10 liters injected over approximately 10 minutes with a concentration of 10^4 to 10^5 oocysts per milliliter. The three different pretreatment processes were challenged at the flow rate described above for approximately 120 minutes, except for the Actiflo unit, which was challenged for approximately 40 minutes because of its low detention time and higher loading rate.

The challenged feed stream (influent) and effluent were collected and enumerated. Initial experiments were utilized to determine if grab samples or membrane disk filtration (EPA Method 1622) would be optimum for isolation and enumeration of the effluent stream for *Cryptosporidium* oocysts. Membrane disk filtration is capable of concentrating 20 liters into a small 40-50 milliliter concentrate. The concentrate may be further processed using immunofluorescence microscopy with monoclonal antibodies (indirect fluorescent antibody — IFA) specific to the oocyst cell wall.

One-liter grab samples taken over a time series during the challenge run were processed by centrifugation and enumerated by IFA microscopy. Influent samples were collected for each of the processes from a sampling port located after the injection port and before the particular process. One-liter grab samples of the effluent were collected every 20 minutes for 140 minutes to evaluate the DAF and Super-P units. The effluent sampling for the Actiflo consisted of one-liter-grab samples every 3 to 5 minutes for 40 minutes. Three 20-liter effluent samples were also collected to reduce the dilution potential due to the higher flow in relation to the other processes.

The influent samples were evaluated utilizing a 1-milliliter aliquot from the collection vessel and using an IFA technique and epifluorescence microscopy for the detection of *Cryptosporidium* oocysts. Analysis of the effluent samples was accomplished by centrifugation followed by IFA. The 20-liter carboy samples were concentrated using a 142-mm polycarbonate membrane disk filtration method (EPA method 1622) and enumerated using the aforementioned IFA technique.

Table 2. Turbidity Data – Clarified Water

Process	Maximum	Minimum	Average	Standard Deviation	Coefficient of Variation
Actiflo	4.1	0.22	0.42	0.46	1.1
Super-P	4.8	0.31	1.28	0.93	0.73
DAF	2.8	0.27	1.11	0.57	0.51
Dorr-Oliver	1.8	0.09	0.69	0.30	0.43

Preparation of Spiking Solution

The *Cryptosporidium* oocysts were purchased from Pleasant Hill Farms (Troy, Idaho) at a concentration of $1x10^8$ oocysts/milliliter. They were less than 30 days old. At the University of South Florida, the ordered stock solution was enumerated by a hemacytometer utilizing and epifluorescence microscopy to determine the exact concentration level. The oocysts were formalized prior to use in the field.

Sample Collection and Analysis

Samples were collected and enumerated from both the feed stream (influent) and the effluent stream. Initial experimentation determined that grab samples and membrane disk filtration would be optimum for isolation and enumeration of the permeate stream for *Cryptosporidium* oocysts.

Grab Sample Method: A one-liter sterile sample bottle was used to take a discrete water sample for analysis. The grab samples from the feed stream were collected in a 50-milliliter polypropylene centrifuge tube and taken at approximately 0, 2, 6, 10, and 12 minutes to determine the mean spike concentration and the total loading and to determine whether the feed concentration remained fairly constant. The grab samples from the effluent stream were collected in a 20-liter carboy or a one-liter polypropylene bottle, depending on the process, and taken every 20 minutes for approximately 180 minutes, except for the Actiflo unit because of its 13-minute detention time. Once the optimum concentration methodology (grab versus membrane disk filtration) was identified, that method was used for the remainder of the challenges.

Analysis of grab samples from the effluent for *Cryptosporidium* oocysts was accomplished by concentrating the one-liter-grab sample through centrifugation. The concentrate was analyzed by the IFA technique for detection of *Cryptosporidium* oocysts. Influent samples had a high enough concentration to evaluate the levels of oocysts by taking a 1 ml to 10 ml aliquot and using the IFA technique.

Membrane 142 mm Disk Filtration, EPA Method 1622: Effluent samples were collected in a 20-liter sterile carboy for membrane disk filtration analysis. Membrane disk filtration employs passing water through a 1.0 mm, 142 mm, polycarbonate membrane placed in a disk filter. The filter is then eluted by hand washing and sonication and concentrated by centrifugation. The oocysts were enumerated by the IFA technique.

Sample Storage and Transportation

All water samples were placed on ice and transported to the Environmental Laboratory at the University of South Florida within 24 hours for further processing and analysis.

Summary of Clarified Water Data

Table 1 summarizes the particle data for the clarified water collected over the course of the study, including the particle data collected during the *Cryptosporidium* spikes. The process stability for each clarification technology was assessed by comparing both the standard deviation and coefficient of variation for each of the parameters. The coefficient of variation was calculated by dividing the standard deviation by the average.

Table 1. Particle Data – Clarified Water
(Total particles per ml, >2μm)

Process	Maximum	Minimum	Average	Standard Deviation	Coefficient of Variation
Actiflo	97	14	43	21	.49
Super-P	11,257	125	1,595	2,209	1.38
DAF	5,934	212	2,467	1,880	0.76
Dorr-Oliver	4,685	171	680	1,213	1.78

Of the three high-rate processes and the Dorr-Oliver unit, Actiflo had the most stable performance with the lowest standard deviation and coefficient of variation. The average clarified water particle removal for Actiflo was 1.5 to 2 orders of magnitude better than the other processes tested.

Table 2 summarizes the turbidity data for the clarified water. Again the Actiflo process had the highest removal and the lowest standard deviation of the three high-rate processes tested. In this case the Actiflo process had a higher coefficient of variation since it had a much lower turbidity average. The other process which indicated a stable performance for turbidity removal was the Dorr-Oliver unit, which is a conventional process similar to Actiflo, but without sand and operated at much lower surface loading rates.

Based on the data summaries in Tables 1 and 2, Actiflo provided high levels of particle and turbidity removal with the highest level of process stability of the three processes tested. The only other process, which demonstrated process stability similar to Actiflo for turbidity removal, was the existing Dorr-Oliver unit. The Actiflo process achieved its higher level of process stability and performance, when compared to the Dorr-Oliver unit, while operating at approximately 30 times the loading rate.

Summary of *Cryptosporidium* Spiking Results

The results of the challenge study on each of the three high-rate clarifiers are summarized in Table 3. It is important to note the reported log removals for each of the processes was for clarification only. By enumerating the remaining oocysts in the clarified water, a true side-by-side evaluation between the three clarification processes was possible.

All three clarification technologies were effective in removing *Cryptosporidium* via coagulation and clarification. With the exception of the Super-P challenge No. 2 and the Actiflo challenge No. 1, good reproducibility was achieved among the triplicate spikes. The following will detail some of the operating conditions that occurred during these challenge tests.

Super-P: Challenge Nos. 1 and 3 for the Super-P suggest that this clarification process is very effective in removing *Cryptosporidium* oocysts. The average for these two challenges is a 3.61 log removal. During challenge No. 2, there was a coagulation upset during the spike which caused the Super-P to loose the stability of its blanket. Due to this upset, the removal for this challenge was 1.79-log. This data strongly suggests the importance of upstream chemistry and coagulation for a clarification technology to function effectively.

Dissolved Air Flotation: The DAF process was operating under the same conditions (no upsets) during each spike. Since there were no process variations during the challenges, the DAF data illustrate that the spiking methodology used was repeatable. Although the DAF process was effective in removing oocysts with an average of 2.86-log between the three spikes, it did not achieve log removals as high as the other two clarification technologies.

Actiflo: Challenge Nos. 2 and 3 for Actiflo suggest that this process is also very effective for removing *Cryptosporidium* oocysts. The first challenge for the Actiflo was skewed since insufficient oocysts were injected into the raw water stream. The data in Table 3 illustrate that the influent oocyst concentration was 2 orders of magnitude lower than in the other challenges. The reason for the under-estimation of the required influent concentration was the high flow rate for the Actiflo unit, which was approximately 300 gpm. After the first spike, this problem was corrected. The average removal for the challenge Nos. 2 and 3 is 3.91-log, which suggests that under the proper coagulation conditions, the Actiflo process is very effective in removing *Cryptosporidium*.

Table 3. Summary of Total Loading, Percent Removal and Log_{10} Removal

Clarifier Type and Challenge #	Total Influent Concentration (Total oocysts injected)	Total Effluent Concentration (Total oocysts)	Percent Removal	Calculated Log_{10} Removal
Super-P				
#1	1.052×10^8	1.9682×10^4	99.9812	3.7279
#2	8.385×10^7	1.3531×10^6	98.3863	1.7922
#3	6.1998×10^7	1.9682×10^4	99.9683	3.4983
Dissolved Air Floatation				
#1	2.0705×10^7	2.4527×10^4	99.8815	2.9264
#2	2.6315×10^7	8.1756×10^4	99.6893	2.5077
#3	2.9483×10^7	2.0439×10^4	99.9307	3.1591
Actiflo				
#1	6.6345×10^6	2.0133×10^4	99.6965	2.5179
#2	2.2171×10^8	1.5901×10^4	99.9928	4.1444
#3	8.3686×10^7	1.7377×10^4	99.9792	3.6827

These data suggest that under proper coagulation conditions, all three of the clarification technologies were effective in removing *Cryptosporidium* oocysts with the microsand ballasted clarifier achieving the highest level of removal. The average removals among the three processes ranged from 2.86 to 3.91 log removal. In addition, for this water, the clarified water quality in terms of total particles correlated somewhat to the levels of *Cryptosporidium* removed as illustrated in Table 4.

Table 4 – Comparison Between Particle Levels and Cryptosporidium Removal

Process	Average Clarified Water Particles (total >2mm)	Average *Cryptosporidium* Log Removal
Actiflo	43	3.91 log
Super-P	1,595	3.61 log
DAF	2,467	2.86 log

Although there is no correlation between total particle removal and *Cryptosporidium* oocyst removal, the above data suggest that optimizing coagulation/clarification to maintain lower levels of particles in the clarified water should be a reasonable indicator for identifying higher levels of treatment performance. ■