Protecting Our Water Environment

Metropolitan Water Reclamation District of Greater Chicago

MONITORING AND RESEARCH DEPARTMENT

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STICKNEY PHOSPHORUS TASK FORCE

TECHNICAL MEMORANDUM NO. 2

ENHANCED BIOLOGICAL PHOSPHORUS REMOVAL APPROACH AT THE STICKNEY WATER RECLAMATION PLANT AND DO CONTROL SUMMARY

October 2014

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FORWARD

The Metropolitan Water Reclamation District of Greater Chicago (MWRD) recognizes the value of phosphorus as a non-renewable resource. In an effort to optimize the sustainable removal of phosphorus from its wastewater influents and the subsequent recovery of phosphorus in various forms suitable for use as an agronomic fertilizer, the MWRD initiated a Phosphorus Removal and Recovery Task Force in 2012. The Task Force initiated a study phase at several of the MWRD's Water Reclamation Plants (WRPs) to evaluate the feasibility of implementing enhanced biological phosphorus removal and to develop operational guidelines for optimizing its effectiveness. The Task Force has created WRP specific study workgroups that are focused on each of the WRPs that have been identified to participate in this initiative. As the workgroups complete various phases of their studies and evaluations they are documenting their findings and recommendations in technical memoranda. These memoranda are written by the WRP specific workgroups and vetted by the Task Force before being published. Their purpose is to capture the state of knowledge and study findings and to make recommendations for implementation of enhanced biological phosphorus removal as they are understood at the time the memoranda are published.

DISCLAIMER

The contents of this technical memorandum constitute the state of knowledge and recommendations developed by the MWRD's Phosphorus Task Force at the time of publication, and are subject to change as additional studies are completed and experience is attained, and as the full context of the MWRD's operating environment is considered.

Technical Memorandum 2

Date: December 12, 2013

To: Phosphorus Task Force & Advisory Committee

From: Phosphorus Study/Planning Team

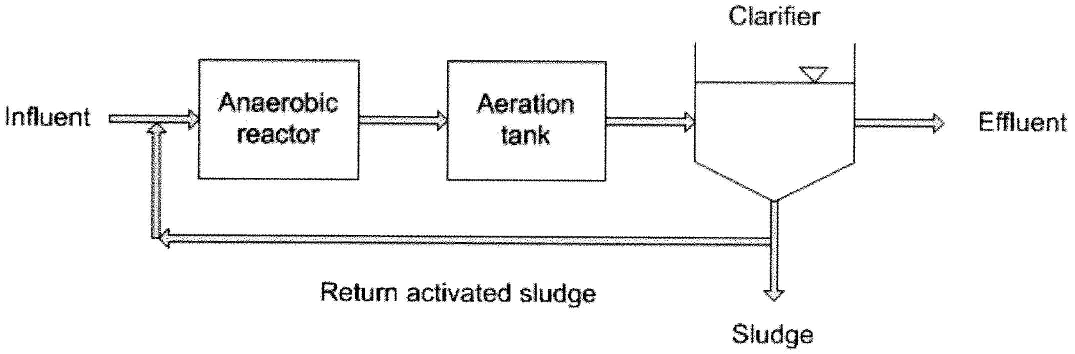
Subject: Enhanced Biological Phosphorus Removal Approach at the Stickney Water Reclamation Plant and DO Control Summary

PHILOSOPHY OF EBPR

Enhanced biological phosphorus removal (EBPR) is performed by phosphate-accumulating organisms (PAOs), which are naturally occurring bacteria present in aerobic activated sludge processes. Their growth is encouraged by cycling them between anaerobic and aerobic conditions. PAOs store energy as polyphosphates. These contain high-energy bonds and function like energy storage batteries. In the absence of oxygen (O), or under anaerobic conditions, the PAO polyphosphate bonds are broken to provide the energy to uptake volatile fatty acids (VFAs) forming intercellular poly-β-hydroxyalkanoates (PHAs) and causing P release. In the subsequent aerobic zone, or in the presence of O, PAOs obtain energy from breaking stored PHAs, uptake large amounts of P into their cells, and again store energy as polyphosphates.

With the traditional plug flow reactors at the District, this philosophy can be applied as illustrated in Figure 1. In a fully functioning EBPR process, the return activated sludge (RAS) is abundant with PAOs and is combined with battery influent (primary or raw). In the subsequent anaerobic and aerobic zones, luxury uptake of phosphate occurs, as suggested above. The mixed liquor is then separated in the secondary clarifier and part of the PAO-rich sludge is wasted, causing net-removal of phosphorus from the system.

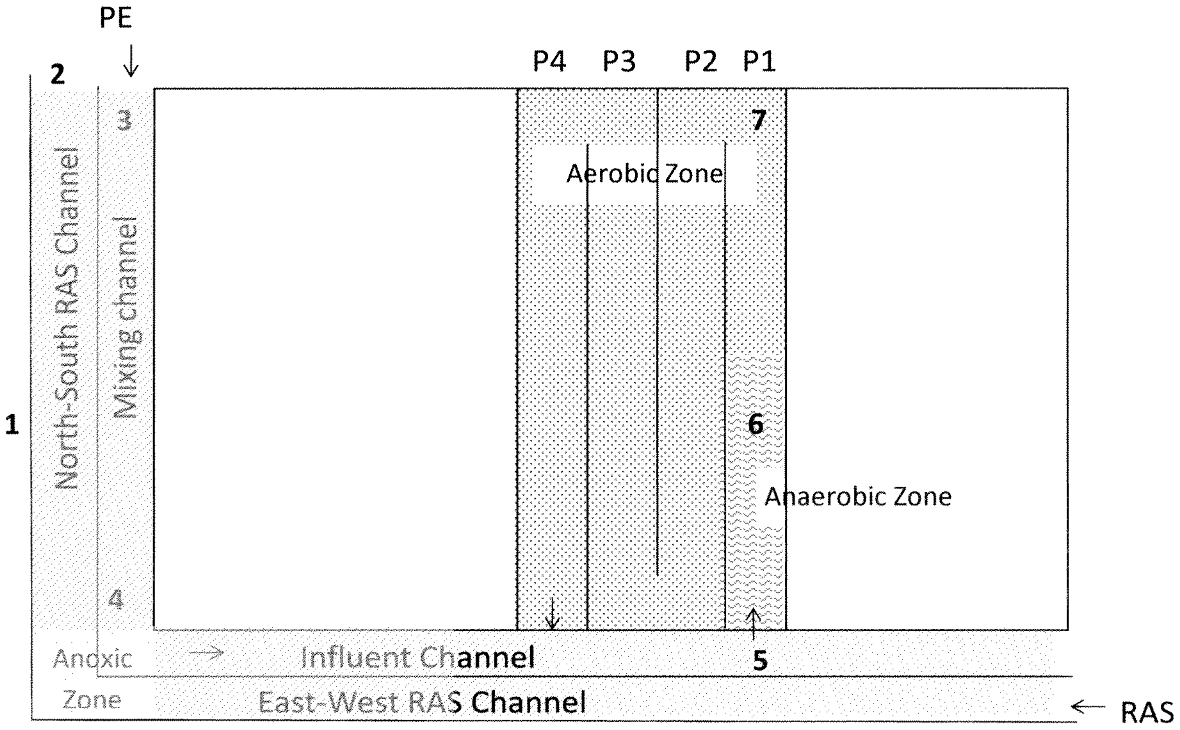
FIGURE 1 – EBPR FLOW DIAGRAM



STICKNEY EBPR DEMONSTRATION SET UP

Given the above philosophy, Battery D operations were modified May 2012 to accommodate both the anaerobic zone followed by the aerobic zone in sequence. However, because Stickney is a nitrifying plant, it was necessary to implement an anoxic zone ahead of the anaerobic zone. In this anoxic zone, the nitrate (NO_3) being returned with the RAS can be denitrified. The EPBR battery diagram is illustrated in Figure 2; numbers 1 through 7 represents monitoring locations discussed in the DO improvement section. At the inception of this demonstration project, the three zones described were generated through modifying the air flow in the air lift, RAS, mixing, and feed channels and the first half of pass 1 in each aeration tank.

FIGURE 2 – SCHEMATIC OF SWRP EBPR BATTERY



CRITERIA

There are several key parameters that help determine the success of EBPR operations. When these criteria are met consistently, EBPR has the potential to decrease TP in the effluent to well below 1 mg/L. Table 1 summarizes optimal EBPR parameters described; their significance is described below.

TABLE 1: OPTIMAL CONDITIONS FOR EBPR

Parameter	EBPR Design Range/Target
DO anaerobic and anoxic zone (mg/L) [1]	0
DO beginning of aerobic zone (mg/L)[2]	1–2
NO_3-N anaerobic zone (mg/L)[2]	0
COD:TP anaerobic zone[2]	>45
BOD:TP anaerobic zone[2]	>25
VFA:TP anaerobic zone[2]	7-10
pH anaerobic[3]	>5.5
pH aerobic[2]	>6.9
SRT (days)[1]	~4
HRT anaerobic zone (hours)[1]	0.5-1.5
HRT aerobic zone (hours) [1]	4-8
MLSS (mg/L) [1]	3,000-4,000
Q_{RAS}/Q_{INF}[1]	0.25-1.0
Temperature (°C) [2]	5–28

1: WEF and ASCE/EWRI. 2006. *Biological Nutrient Removal (BNR) Operation in Wastewater Treatment Plants, WEF Manual of Practice No. 29, ASCE/EWRI Manuals and Reports on Engineering Practice, No. 109.* New York: WEF Press, McGraw-Hill.

2: WEF, Nutrient Removal Task Force. 2011. *Nutrient Removal: WEF Manual of Practice No. 34.* New York: McGraw-Hill.

3: Randall, C. W. and R. W. Chapin. 1997. *Acetic Acid Inhibition of Biological Phosphorus Removal.* Water Environment Research. 69(5):955–960.

Dissolved Oxygen

The dissolved oxygen (DO) in the anaerobic zone must be sufficiently low for PAOs to compete for the readily biodegradable carbon. If DO is present in the anaerobic zone, aerobic heterotrophic organisms will compete with PAOs for this carbon. Denitrification is also inhibited when DO is present in the anoxic zone; the aerobes will consume carbon with oxygen as an electron acceptor instead of nitrate. At the SWRP, the anoxic and anaerobic zones directly follow the air lifts which carry the RAS back to the aeration tanks; however, being airlifts, considerable DO returns, too, making it difficult to achieve low DO.

Research has also shown that sufficient DO in the aerobic zone of EBPR is crucial to the process. The DO levels in this section drive PHA consumption and P uptake and retention. While DO saturation is unnecessary, a quick increase in DO concentration from the anaerobic portion to above 1 mg/L in the aerobic portion is ideal as most P uptake occurs in the first part of the aerobic zone. In addition, sufficient DO helps prevent P release during final clarifier settling. On the other hand, over-aeration can cause excess DO to be returned to the aeration tanks with the RAS.

Nitrate

Similar to DO, NO_3 can also be used as an electron acceptor. Denitrifiers can out compete with the PAOs for the VFAs in low DO environments. As such nitrate in the anaerobic zone can inhibit EBPR.

Volatile Fatty Acids

As discussed in the 'Philosophy of EBPR', the availability of readily biodegradable organic carbon (i.e., VFAs) in the anaerobic zone is critical to the success of EBPR. VFAs in the primary effluent can be measured directly, but other measures of readily biodegradable organic carbon are often more easily attained. As a proxy for VFA, evaluation of the COD or BOD concentrations can provide a rough approximation of available carbon. Evaluating the readily biodegradable COD (rbCOD) is another more reliable way to assess if there is sufficient carbon for EBPR as some of the COD is fermented in the anaerobic zones. These organic metrics are often used to develop ratios relative to TP as a measure of the capability of an EBPR system.

pH

pH under 6.5 can reduce PAO activity and even inhibit EBPR. Fortunately, robust continuous flow biological P removal systems commonly experience a large pH swing between the anaerobic and aerobic zones (e.g., from 7.2 ±0.2 to 8.4 or more), and pH control is largely unnecessary for EBPR operations.

HRT & SRT

In general, a minimum SRT of three to four days is sufficient for EBPR in temperate climates; longer SRTs are needed for colder temperatures. If the SRT becomes too long, however, the quality of the effluent will decrease, because endogenous respiration will cause release of P as biomass degrades. The SRT level at which this secondary release occurs is site specific based on the kinetics of the biomass. As such, the minimum SRTs to support phosphorus removal are suggested in Table 1. However, P removal SRT minimums are often less than the minimum design nitrification SRTs; the greater of these two are used for the system.

Anaerobic zone HRT is also a factor in EBPR. In the anaerobic zone, the HRT allows for sufficient time for the fermentation of non-VFA rbCOD to VFAs and for VFA uptake and storage. If adequate concentrations of VFA are entering the system from outside of the anaerobic zone, a lower anaerobic HRT can be used as the VFA uptake and storage is a relatively fast process.

MLSS

The mixed liquor suspended solids (MLSS) concentration is another parameter that can be used in the control of EBPR systems, although it must be balanced with a minimum SRT. With a higher MLSS, there is also an increase in the PAO population, which benefits the entire system.

RAS Flow

The RAS flow to primary effluent flow ratio is an important consideration largely because of the DO and NO_3 returned to the system from the RAS, the influent TP from the primary effluent stream, and the carbon available for removal of the TP and NO_3. After the primary effluent and RAS flow mix, the available rbCOD is utilized for both TP and NO_3 removal, making both the concentrations and the flows from both critical.

Temperature

Temperatures above 20°C stimulate glycogen accumulating organism (GAO) carbon uptake rates more than PAO uptake rates; GAOs have a similar mechanism for uptaking VFAs in the anaerobic zone as PAOs without the benefit of P uptake in the aerobic zone. As the temperatures become even higher (i.e., around 30°C), the GAOs can dominate because of their increased uptake rates and can have an adverse effect on P removal. Low temperatures can also slow reaction rates and lower P removal, although poor P removal is usually caused by reduced carbon availability or increased DO and NO_3 inputs to the anaerobic zone in low temperatures.

APPROACH TO INCREASE P REMOVAL

The initial goal given to the Study and Planning Team was to examine if the potential effluent total phosphorus (TP) concentration permit limit of 1.0 mg/L as a monthly average could be reached through making changes to aeration and operations within the confines of the existing infrastructure. For example, the low DO requirements had to be balanced with the use of the air for mixing purposes.

The progression of Phases is outlined below:

- Phase I: Initial DO reduction in the RAS channel, mixing channel, influent channel, and the first halves of Pass 1 in each tank. Air input was minimal and aimed to maintain suspension of solids.
- Phase II: Beginning of air improvements. Turned off every other valve completely in mixing channel while other valves kept at minimum.
- Phase III: Increased MLSS to consistently target around 3,500 mg/L, further air decreases in RAS and mixing channel (turned off all air valves), and increased air in aerobic zone in second halves of first pass in each tank (fully opened all air valves).
- Phase IV: Same as Phase III and also held primary sludge in preliminary tanks for longer in attempt to generate VFAs from sludge. Air adjustments to lower the DO at the end of the anaerobic zone were made.

Data from each phase is presented in Table 2. With air adjustments and other changes, the average effluent TP of Battery D improved through each phase from 1.16 mg/L in Phase I to 0.42 mg/L in Phase IV; P removal efficiency averaged 76% in Phase I and improved to an average of 91% in Phase IV.

TABLE 2: SUMMARY OF PARAMETERS AFFECTING EBPR IN BATTERY D

	Phase I (5/1/12-9/12/12)	Phase II (9/13/12-10/9/12)	Phase III (10/10/12-12/12/12)	Phase IV (1/28/13-9/30/13)
Influent TP (mg/L)	4.91	3.69	4.17	4.89
Battery D Effluent TP (mg/L)	1.16	1.42	0.90	0.42
P Removal Efficiency (%)	76.4	61.5	78.4	91.4
Influent Flow (MGD)	193	112	133	172
RAS/Influent Flow	0.98	1.24	1.03	0.97
BOD:TP @ PE	24.1	26.4	27.2	29.2
MLSS (mg/L)	3343	2224	3227	3682
RAS NO3 (mg/L)	6.75	6.72	6.28	5.77

As the improvement approach taken made operational changes in concert with each other, their individual effects on the effluent TP cannot be fully separated. In addition, as is the nature of pilot studies in an uncontrolled environment, the influent to the system cannot be guaranteed to be similar.

However, statistical analyses were performed and showed that the four phases were statistically identical with respect to RAS NO_3-N, influent COD, and influent NO_3-N concentrations; influent BOD concentrations were statistically identical in Phases I – III but statistically higher in Phase IV. Phases I and IV had identical influent TP concentrations, while concentrations in Phase II and Phase III were identical but were statistically lower than Phases I and IV. Finally, influent and RAS flows varied through the four phases. Effluent TP from the test Battery was considered statistically identical in Phases I – III and were statistically higher than Phase IV. Of the parameters chosen for examination, the effluent TP was most influenced by the DO in the various zones and the carbon available to the PAOs, according to the preliminary statistical correlation analyses of the data.

This Technical Memoranda (TM) will focus on the DO parameter – the improvements made to the system with respect to DO and the effects of those changes on the DO and, ultimately, on battery effluent TP. Future TMs will discuss other parameters important to EBPR and affected by the improvement approach including MLSS, Carbon, and Nitrate.

1. DISSOLVED OXYGEN

The changes made to DO went through all four phases as summarized in Table 3.

TABLE 3: SUMMARY OF DISSOLVED OXYGEN IMPROVEMENT IN BATTERY D

	Phase I (5/1/12-9/12/12)	**Phase II (9/13/12-10/9/12)**	**Phase III (10/10/12-12/12/12)**	**Phase IV (1/28/13-9/30/13)**
DO Improvement	Initial DO reduction in the RAS channel, mixing channel, influent channel, and the first halves of Pass 1 in each tank	Turned off every other valve completely in RAS and mixing channel while other valves kept at minimum	Turned off all air valves in RAS and mixing channel and increased air in aerobic zone in second halves of first passes in each tank	Further air improvement in second halves of first passes in each tank

Two sets of DO data were collected during the EBPR implementation period. 1. Continuous DO concentrations measured with a Hach HQ40 DO probe were recorded every 15 minutes for two to three days at each location as identified in Figure 2 during Phases II through Phase IV; and 2. Field grab sample DO data were instantaneously measured with a Hach HQ40 DO probe at each location during the manual sampling events performed one to two times per week since May 2012. It was also observed that the DO readings were different in the diffuser sides of aeration tanks, i.e. DO levels were slightly higher in the diffuser side than the opposite. DO measurements used in the below analysis were all from the diffuser side.

Continuous DO results are discussed below and summarized in Table 3. No continuous DO data was collected in Phase I.

- **Anoxic zone:** In Phase II, with every other coarse bubbler valve off in the RAS and mixing channels, Table 3 shows that the anoxic zone (defined as [DO] = 0 mg/L) did not start until the middle of the mixing channel (between Points 3 and 4 in Figure 2). After air in the channels was further reduced in Phase III, the average DO in the middle of the RAS channel (Point 1 in Figure 2) was significantly reduced, from 5.92 mg/L in Phase II to 1.09 mg/L in Phase III. This allowed the anoxic zone to begin by Point 3 in Phase III. In Phase IV, the anoxic zone moved further upstream to Point 2 (Please note that no data was collected at Point 2 during Phase III). Statistical analysis indicated that the DO levels in the middle of the RAS channel were significantly different and lower in Phase II relative to Phase III, and no difference was observed between Phase III and Phase IV.
- **Anaerobic zone:** DO at beginning of the anaerobic zone for the test tank (Tank 4) was 0 mg/L throughout the study as shown in Table 2 (Point 5 in Figure 2). DO was below 0.2 mg/L at Point 4 which would be the beginning of the anaerobic zone for Tank 1. If DO is available in the anaerobic zone, PAOs can metabolize VFAs for cell growth instead of storing VFAs by releasing P using energy from polyphosphate bonds for

subsequent phosphate uptake, thus less EBPR. Aerobic heterotrophs can also compete for carbon using DO as well. Table 3 indicates the average DO at the end of the anaerobic zone (Point 6 in Figure 2) during Phase III the DO was 0.76 mg/L, much higher than the recommended value of 0 mg/L for an anaerobic zone. In Phase IV, air valves near the end of anaerobic zone were adjusted to a minimum while maintaining some level of mixing. The average DO at Point 6 was brought down to 0 mg/L during this phase.

- **Aerobic zone:** In Phase III, the average DO in the aerobic zone, (Point 7 in Figure 2), was 0.42 mg/L. For better EBPR, maintaining a sufficiently high DO (>1 mg/L) at the beginning of aerobic zone is required. PAOs need oxygen to digest the VFAs consumed in the anaerobic zone and to uptake and retain P in the aerobic zone. Maintaining a sufficiently high DO transfer in the aerobic zone enhances process stability and has been found to be a key factor in P removal. In Phase IV, air in the second half of Pass 1 was increased to ensure a high DO at the beginning of the aerobic zone. After this adjustment, the average DO at Point 7 was 3.78 mg/L in Phase IV. Statistical analyses showed the DO levels at the end of aerobic zone are significantly different and lower in Phase III relative to Phase IV.

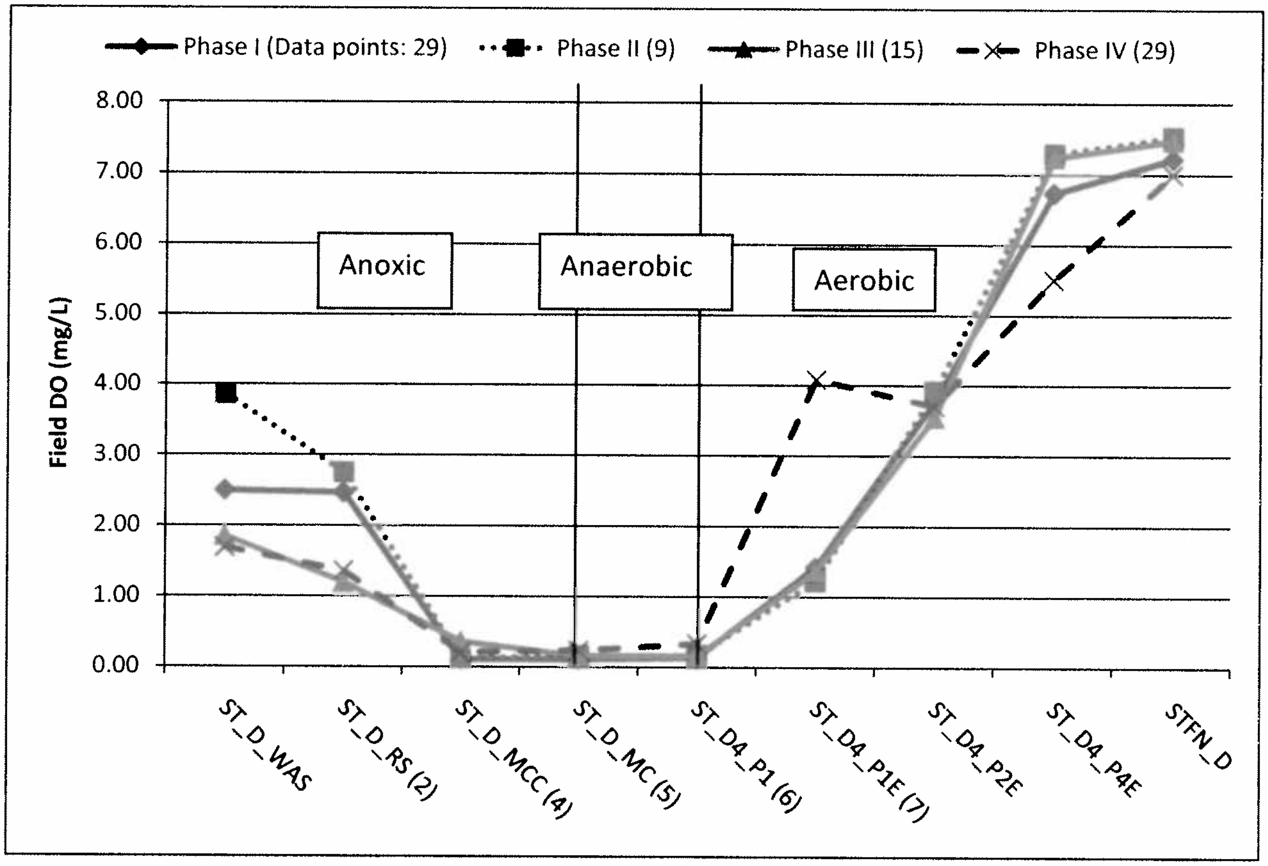
TABLE 3: STATISTICAL DATA OF CONTINUOUS DISSOLVED OXYGEN (mg/L) IN BATTERY D

	RAS_Middle (1)	RAS (2)	MC_Begin (3)	MCC (4)	MC (5)	P1 (6)	P1E (7)
	Phase II						
Min	1.84	4.32	0.04	0.00	0.00	nd	nd
Max	7.07	7.07	0.95	0.00	0.00	nd	nd
Aver	5.92	6.47	0.10	0.00	0.00	nd	nd
	Phase III						
Min	0.00	nd	0.00	0.00	0.00	0.26	0.00
Max	3.79	nd	0.77	0.00	0.00	1.68	1.68
Aver	1.09	nd	0.05	0.00	0.00	0.76	0.42
	Phase IV						
Min	0.00	0.00	0.00	0.00	0.00	0.00	0.88
Max	2.98	0.61	0.12	0.18	0.10	0.00	5.60
Aver	0.91	0.00	0.00	0.00	0.00	0.00	3.78

*nd: no data

Figure 3 shows the average field grab DO profile during each improvement phase. The number of data points for each improvement phase is shown in the footnote in Figure 3. DO levels in the anoxic zone were improved through Phases II and III; and DO levels in the anaerobic and aerobic zone were improved in Phase IV, as indicated in Figure 3. In Phase IV, further air improvement in the beginning of the aerobic zone was done. As shown in Figure 3, DO levels were significantly improved in the beginning of aerobic zone, and statistical analyses showed the same results. However, backwash could be occurring in the end of anaerobic zone due to the aerobic zone adjustments as DO at P1E were slightly higher in phase IV.

FIGURE 3. FIELD GRAB DO PROFILE IN BATTERY D DURING EBPR IMPROVEMENT PHASES*



***Sampling points for Phase I: 29; Phase II: 9; Phase III: 15 and Phase IV: 29.**

CONCLUSIONS

At this point, the DO is considered to be optimized with respect to the current infrastructure as the levels in all zones meet recommended EBPR criteria. However, further DO control in the different zones may be improved by baffles and mixers. At this time, no baffle or mixer testing will be performed at Stickney, but tests are being performed at the Kirie WRP which is also undergoing EBPR changes.