New Aeration Controls for Improved BNR Performance and Cost Savings

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ABSTRACT

Upper Blackstone installed 8 hyperbolic mixer/aerators and 28 iris diaphragm valves and instituted a new aeration control strategy to fine-tune DO control within its A^2/O process. The mixer/aerators have yielded substantial reductions in mixed liquor recycle dissolved oxygen (DO), reducing supplemental carbon by approximately 50 percent. The blowers can operate in either a flow most open valve (MOV) or pressure MOV mode. Results are presented from six months of flow-based aeration control with respect to meeting the DO set points, system flow, system pressure and overall stability. This paper also presents design recommendations and lessons learned regarding modulating valve type and MOV programming fail-safes.

KEYWORDS: Air Control Valves, Most Open Valve Control, Nutrient Removal, Automation, Energy Conservation/Management

INTRODUCTION

Upper Blackstone Clean Water (Upper Blackstone) in Millbury, Massachusetts owns and operates an enhanced biological nutrient removal (EBNR) facility with an anaerobic/anoxic/oxic (A^2/O) process designed for 170,000 m^3/day (45 million gallons per day [mgd]) average daily flow. The facility was originally designed to meet or exceed effluent quality of 8 to 10 mg/L total nitrogen (TN) and 0.75 mg/L total phosphorus (TP), but more stringent permit limits as shown in **Table 1** were issued in 2012.

Table 1. Upper Blackstone 2012 NPDES Nutrient Permit Limits

Parameter	Effluent Limit	
Total Nitrogen (mg/L)		
May - October	5.0	Monthly average
November - April	Report	
Total Phosphorus (mg/L)		
April - October	0.1	Maximum 60-day rolling average
November - March	1.0	Monthly average

Upper Blackstone implemented numerous interim measures from 2012 through 2015, resulting in substantial improvements to effluent quality, which are reported in Neville et al (2015). Upper Blackstone subsequently undertook a $25 million nutrient upgrade project to make permanent the most successful interim measures, including a permanent supplemental carbon feed system and upgrades to the aeration control system to provide tighter EBNR control.

The driver for the aeration upgrade was to improve dissolved oxygen (DO) control compared to the existing system that relied on manually-operated butterfly valves for each of the 28 droplegs. **Table 2** summarizes the tapered DO set points Upper Blackstone targeted for process control, as well as the aeration control equipment its operators had available to distribute airflow and control the DO within specific fine bubble diffuser grids prior to the recent aeration upgrade. The only automated components in the distribution system prior to the upgrade were two 750-mm (30-inch) modulating header valves linked to a single DO set point for Grid 3. Upper Blackstone could either select the Grid 3 DO probe for a specific bioreactor or could use the average of the Grid 3 DO probes for all operating bioreactors to determine how to modulate blower output.

Table 2. Control Equipment Used to Maintain Tapered DO Set Point Targets Prior to the Aeration Upgrade Project

Location	Valve Size	Valve Type	Actuator Type	DO Set Point	Flow Measurement
Battery Pipe Headers					
Bioreactor 1 and 2	30-inch	AWWA butterfly	Motor operator	n/a	Thermal mass
Bioreactor 3 and 4	30-inch	AWWA butterfly	Motor operator	n/a	Thermal mass
Droplegs for Each Bioreactor (x4)					
Zone F1 - Grid 3	12-inch	AWWA butterfly	Manual handwheel	3 mg/L	Pitot tube [1]
Zone F2 - Grid 4A [2]	8-inch	AWWA butterfly	Manual handwheel	2 mg/L	Pitot tube [1]
Zone F2 - Grid 4B [2]	8-inch	AWWA butterfly	Manual handwheel	2 mg/L	Pitot tube [1]
Zone F3 - Grid 5A [2]	8-inch	AWWA butterfly	Manual handwheel	n/a [3]	Pitot tube [1]
Zone F3 - Grid 5B [2]	8-inch	AWWA butterfly	Manual handwheel	n/a [3]	Pitot tube [1]
Zone F4 - Grid 6	8-inch	AWWA butterfly	Manual handwheel	1 mg/L	Pitot tube [1]
Zone G	8-inch	AWWA butterfly	Manual handwheel	0.5 mg/L	Pitot tube [1]

Notes:

1. The pitot tubes only have local indication of air flow; not connected to SCADA.
2. Grids 4A/4B and Grids 5A/5B are a grid-within-a-grid configuration, meaning that two aeration droplegs serve diffuser grids that occupy the same footprint within the bioreactor.
3. Grids 5A/5B do not have a DO probe. In addition, sometimes the valve to either Grid 5A or Grid 5B is fully closed, depending on bioreactor influent load.

With only manual control of the 28 dropleg valves, it was difficult to maintain the tapered DO set points in the plug flow reactors due to diurnal and seasonal variability in oxygen demand. Excursions of high DO were common, which negatively impacted denitrification. The primary objective of the aeration upgrade was to provide tighter DO control, and thus improved EBNR performance.

A secondary goal for the aeration upgrade was to reduce energy and carbon costs. The system was designed with the intent of reducing operating pressure by refining valve control and implementing either a flow-based blower control scheme or a tighter floating pressure-based blower control scheme. Mixer/aerators were installed in the effluent end of the bioreactors to decouple process aeration from mixing in a zone that typically has low oxygen demand, to minimize the DO returned in the internal mixed liquor recycle. The intent was to reduce the quantity of supplemental carbon fed to the anoxic zone to achieve nitrogen removal.

This paper presents the updated aeration equipment and control systems which were installed between 2017 and 2019 to improve the Upper Blackstone A^2/O process and how the facility has performed since starting up in December 2018. This paper also discusses benefits of the advanced controls with respect to supplemental carbon use, blower energy requirements, and EBNR performance (effluent TN and TP).

METHODOLOGY

Oxygen demand at Upper Blackstone is met using four 600-kW (800-HP) single-stage integrally-geared centrifugal blowers with inlet guide vanes (IGVs) and variable diffuser vanes (VDVs). The local control panels (LCPs) supplied with the blowers provide several functions, including: optimize blower efficiency while varying blower output using dual-vane control; monitor and protect the blowers during start-up, shutdown and normal operation; and provide local control of the blowers and individual skid components. Prior to the aeration upgrades, blower output was controlled via a floating pressure set point calculated based on the position of the most open valve (MOV) of the two modulating header control valves. The existing blowers have sufficient capacity and turndown and were not modified for the aeration upgrade.

Figure 1 provides an overview of the new aeration control system when using the flow control mode. The LCPs continue to provide the same functionality, but a new master blower control panel (MBCP) has been added to (1) distribute airflow to maintain DO set points and (2) control blower output and sequencing.

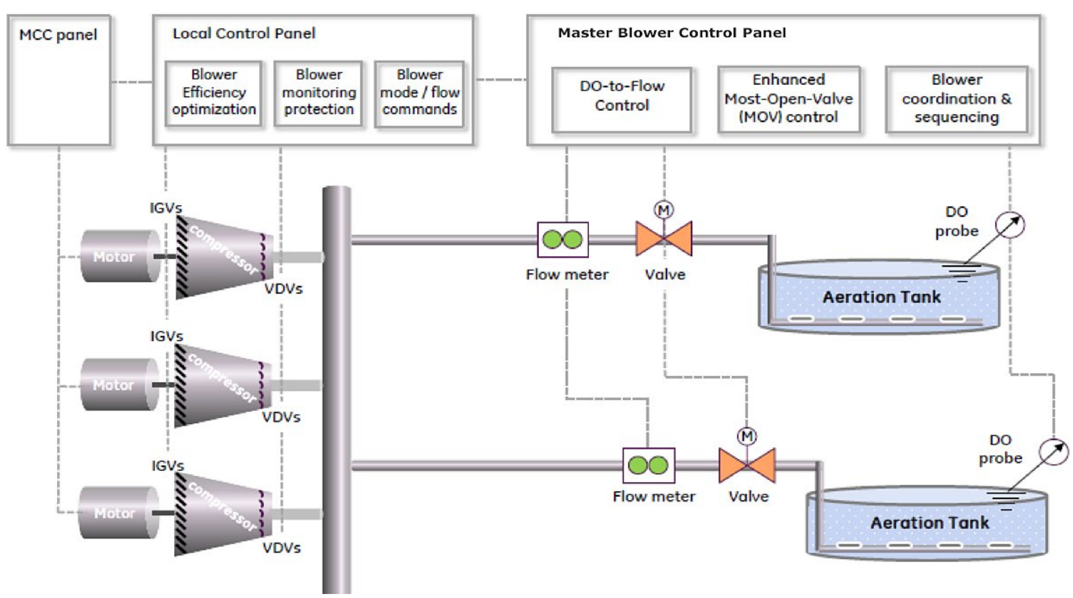

Figure 1. Overview of New Aeration Control System

The new aeration equipment installed includes the following:

(1) Replacement of the 28 manual aeration dropleg valves and pitot tubes with motor-operated iris diaphragm valves and thermal mass flow meters furnished by Egger Pumps;

(2) Replacement of the fine bubble diffusers in Zone G (the final aerobic zone of the A^2/O process) with hyperbolic mixer/aerators by INVENT Environmental Technologies; and

(3) Installation of an MBCP equipped with MOV controls for the 20 control zones, along with the flexibility to incorporate ammonia-based aeration control (ABAC) in the future, supplied by Howden Roots.

Figure 2 depicts the A^2/O process configuration for each of the four bioreactors at Upper Blackstone, with the new aeration equipment installed. It also identifies the locations of other pertinent online analyzers and the supplemental carbon feed location.

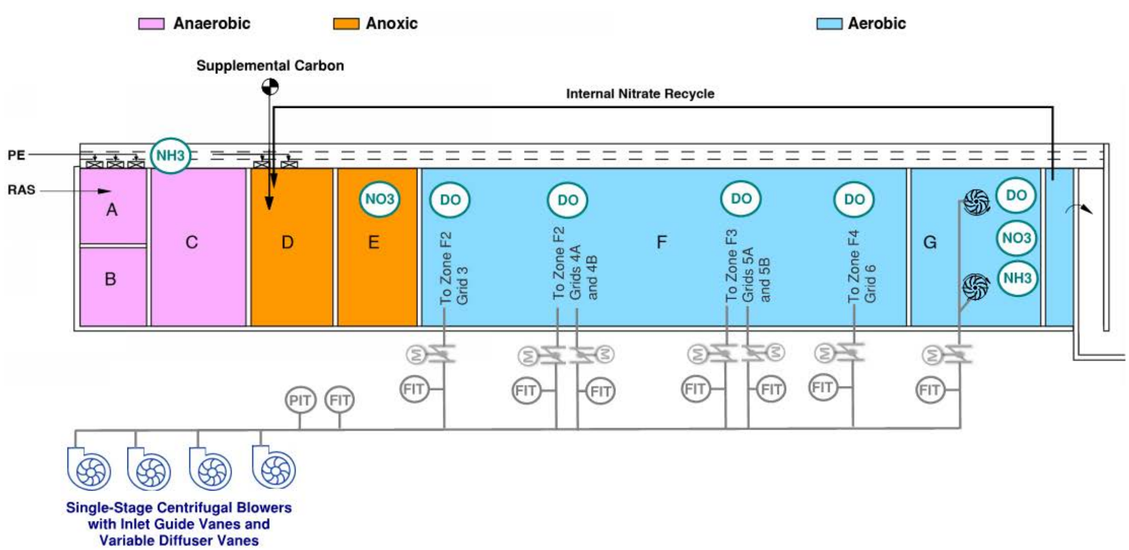

Table 3 summarizes the tapered DO set points Upper Blackstone currently targets for process control, as well as the new aeration control equipment being used to automatically distribute airflow to the bioreactors and control the DO to specific DO control zones.

The MBCP is programmed with four modes to control blower output:

(1) Auto MOV Flow Control;
(2) Auto MOV Pressure Control;
(3) Manual Flow Control;
(4) Manual Pressure Control.

Error-based blower flow control with MOV was used as the primary control strategy for Upper Blackstone's controls upgrade. Each individual control zone demands a certain quantity of air to maintain the DO level for a particular zone. By summing the individual control zone flow demands, the exact quantity of total system flow can be determined in order to meet process needs. However, if there are any side flows that are not measured, the total flow demanded in the DO control zones might not match the total required blower flow. In order to account for unmeasured flows, error-based flow control was used.

Table 3. Control Equipment Used in each Bioreactor to Maintain Tapered DO Set Point Targets After the Aeration Upgrade Project

Location	Valve Size	Valve Type	Actuator Type	DO Set Point	Flow Measurement
Zone F1 - Grid 3	10-inch	Iris diaphragm	Motor operator	3 mg/L	Thermal mass
Zone F2 - Grid 4A [1]	4-inch	Iris diaphragm	Motor operator	2 mg/L [2]	Thermal mass
Zone F2 - Grid 4B [1]	4-inch	Iris diaphragm	Motor operator	2 mg/L [2]	Thermal mass
Zone F3 - Grid 5A [1]	4-inch	Iris diaphragm	Motor operator	1.5 mg/L [2]	Thermal mass
Zone F3 - Grid 5B [1]	4-inch	Iris diaphragm	Motor operator	1.5 mg/L [2]	Thermal mass
Zone F4 - Grid 6	5-inch	Iris diaphragm	Motor operator	1 mg/L	Thermal mass
Zone G	5-inch	Iris diaphragm	Motor operator	0.5 mg/L [3]	Thermal mass

Notes:

1. Zone F2 Grids (4A/4B) and Zone F3 Grids (5A/5B) are a grid-within-a-grid configuration, meaning that two aeration droplegs serve diffuser grids that occupy the same footprint within the bioreactor. Each A and B grid has its own automated dropleg valve that is controlled individually.
2. Zone F2 grids are controlled based on one DO probe, and Zone F3 grids are controlled based on one DO probe. Zone F2 Grids (4A/4B) and Zone F3 Grids (5A/5B) modulate one or two flow control valves depending on the current air flow. If only one flow valve is being used and the flow through this zone rises above an adjustable set point, the second valve is called to open. If both valves are modulating and the total flow falls below an adjustable set point, the lag valve will be commanded to close. When both valves are modulating, the total flow set point is divided by two and assigned to each individual flow control valve.
3. Operators will increase the Zone G set point in response to elevated ammonia concentrations, which can happen during winter months with colder wastewater temperatures.

Blower pressure control with MOV was programmed as a backup control strategy to Flow MOV mode to give Upper Blackstone the flexibility of utilizing either control mode, as well as to provide continuity with the limited floating pressure control scheme utilized since the late 2000s. Flow control is better suited for wastewater aeration control systems for its ability to match variable system demand with blower output. In pressure-based systems, it can be difficult to calculate a header pressure set point which will deliver an optimal amount of flow to the aeration system. If the pressure set point is too high, the DO levels can be maintained but the system wastes energy. If the pressure set point is too low, some control zones will not be able to maintain the required DO levels. Since MOV control calculates flow set points for each zone in order to maintain the DO set points, with Flow MOV control the total required flow output for the DO control zones can be more easily coupled to the blower output compared to Pressure MOV control.

Upper Blackstone's new MBCP uses the well-established control strategy of using cascading control loops for DO and flow control. The system also has the flexibility to remove any single control zone from the overall MOV and flow control algorithm by placing that individual control zone in Manual Mode. When an operator places a control zone into Manual Mode, that valve position can be manually entered from the MBCP operator interface. This gives the operators the flexibility to perform maintenance tasks on the DO probes or flow meters without disrupting the overall operation of the MBCP, blowers, and valves.

The two manual modes are included as a backup for maintenance purposes. In Manual Flow Mode, an operator can enter a constant total flow set point for the system that will set the output of the blowers. In Manual Pressure Mode, an operator can enter a constant system header pressure set point that the blowers modulate to maintain. A variety of fail-safes and programmed limits were incorporated into the programming for the Auto control modes, including the incorporation of operator-adjustable minimum and maximum flow set points for each control zone as well as an adjustable minimum and maximum valve position.

Iris valves were chosen for modulating flow control due to their more linear relationship between flow and valve position and, therefore, the wider stable range for control compared to butterfly valves. The authors presented a detailed comparison of different types of control valves at WEFTEC 2017 (Doody and Neville, 2017), including iris valves, jet valves, square diaphragm valves, and high performance butterfly valves.

The range of design air flow rates for each aeration dropleg was developed using design year (2040) maximum day and current minimum day 5-day biochemical oxygen demand (BOD_5) and total Kjeldahl nitrogen (TKN) loads. The distribution of oxygen requirements for each diffuser grid was determined using steady state BioWin simulations (EnviroSim, Hamilton, Ontario). Maximum day air flow rates were based on the projected design year loads with one bioreactor out of service, while minimum day air flow rates were calculated based on current minimum day loads with all bioreactors in service. Where applicable, minimum air flows required for mixing with diffusers were considered in the design criteria. Minimum air flows based on airflow per diffuser were checked, but this did not govern for any control zone.

RESULTS AND DISCUSSION – MIXER/AERATORS

Two 30-HP hyperbolic mixer/aerators were installed in the final aeration zone (Zone G) of each bioreactor to decouple mixing from process oxygen requirements, thereby allowing Upper Blackstone to target low DO concentrations and maximize anoxic zone denitrification. The mixer/aerators can operate in Mixing Only mode or operate in Aerating mode with low air flow. Variable frequency drives (VFDs) were provided for each mixer/aerator to reduce the energy costs for mechanical mixing. The VFDs are used to maintain a torque set point, which is determined based on the air flow into the zone at the time. Lower torque and impeller speeds are required to produce a fine bubble at lower air flows, while higher torque and impeller speeds are needed to produce a similarly-sized fine bubble at the higher air flows.

The first two mixer/aerators were installed in Bioreactor 2 (AT2) in fall 2017, and the remaining six mixer/aerators were installed in Bioreactors 1, 3, and 4 (AT1, AT3, and AT4) during the period from May through November 2018. **Figure 3** demonstrates the low, stable DO concentration achieved in September 2018 in AT1, where mixer/aerators had been installed, compared to AT4, where the fine bubble diffusers had not yet been replaced.

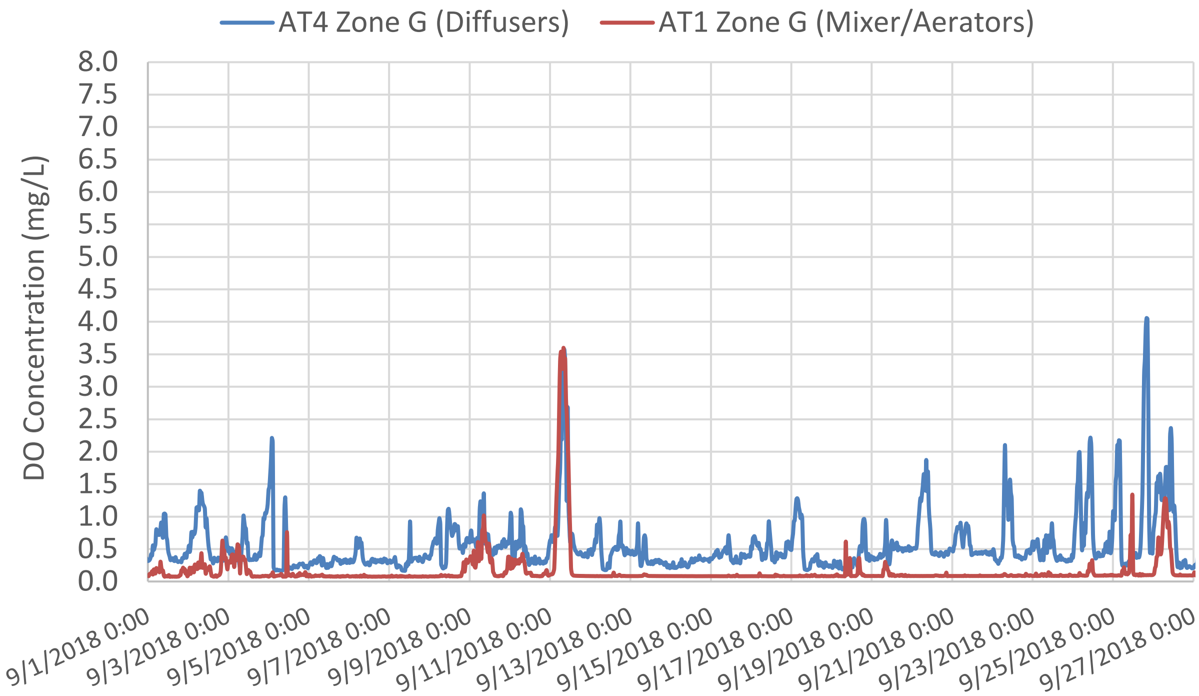

Figure 3. DO trend in final aerobic zone of AT1 compared to AT4

Nitrogen removal performance as demonstrated by bioreactor effluent nitrate plus nitrite (NOx) concentrations is charted in **Figure 4**. During this time period, the plant was achieving nearly complete nitrification (less than 1 mg/L ammonia). Thus **Figure 4** demonstrates that denitrification performance in AT1 with mixer/aerators equaled or exceeded the performance of AT4 with fine bubble diffusers since the effluent NOx concentration was consistently equivalent or lower in AT1.

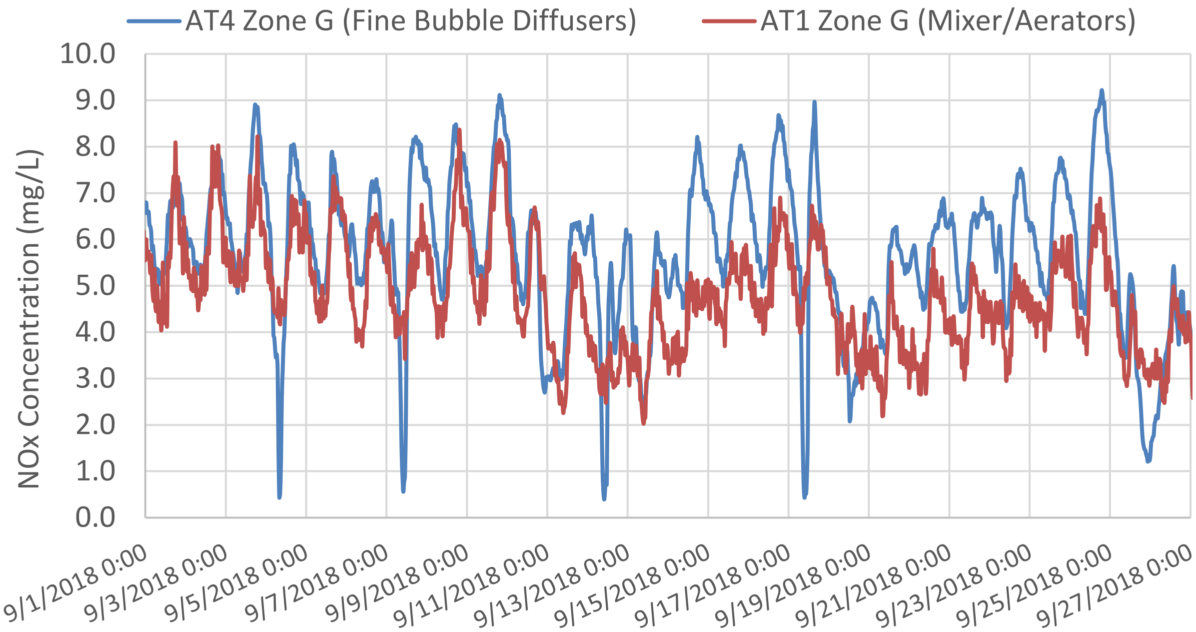

Figure 4. NOx trend in final aerobic zone of AT1 compared to AT4

Supplemental carbon in the form of a glycerin product (MicroC 2000) is fed to each bioreactor using a combination feedback/feedforward control system (Doody et al, 2016). **Figure 5** illustrates the reduction in carbon feed that was achieved by improving DO control and lowering DO concentrations at the end of the oxic zone. The lower effluent DO concentrations minimize the amount of DO returned to the anoxic zone in the internal mixed liquor recycle.

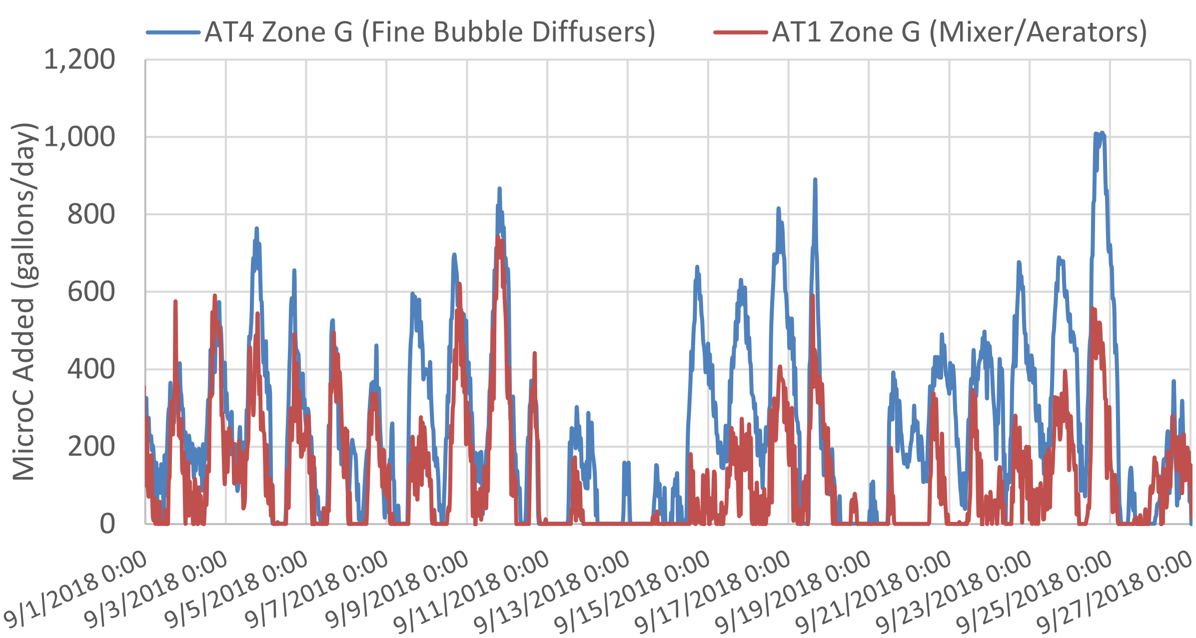

Figure 5. MicroC addition to anoxic zone of AT1 compared to AT4

On wet weather days such as September 11 through 13, September 18, and September 26, the difference in carbon use between the two bioreactors was minimal because the effluent NOx concentrations decreased due to dilution. On the drier weather days during the period shown, the supplemental carbon use in AT4 often exceeded the supplemental carbon needs in AT1 by 50 percent. Upper Blackstone also recently compared MicroC usage in 2018 compared to 2017 before the mixer/aerators had been installed and found that the supplemental carbon quantities had decreased from 177,000 gallons to 48,000 gallons annually, which represents a 73% reduction and an annual cost savings of $258,000 per year (Taher et al, 2019).

The cost savings associated with reduced supplemental carbon must be weighed against the energy costs required to operate the mixer/aerators. The operators have the option to run them in Manual at an operator-entered torque set point or to run in Auto. In the Auto mode, SCADA determines the torque set point based on air flow into the zone based on the VFD torque set points shown in **Table 4**. This table shows the estimated power draw for a single mixer/aerator unit at each torque set point. Note that the actual power draw at a given time varies depending on the air flow; higher air flows reduce the density of the mixed liquor and increase the buoyancy force underneath the mixer blade, therefore reducing power draw at a given torque set point. However, higher torques and speeds are required at higher air flow rates in order to produce a fine enough bubble to accomplish the oxygen transfer required.

Table 4. 30 HP Mixer/Aerator Automation Set Points and Estimated Power Requirements

Zone G Air Flow (scfm)	VFD Torque Set Point (%)	Power Required without Consideration of Air Flow	
		HP	kW
> 1,500	95	28.5	21.3
1,000 – 1,500	83	25.0	18.6
750 – 1,000	65	19.5	48.5
0 - 750	47	13.0	9.7

The mixer/aerators were run in Manual mode in all four bioreactors until all new valves, flow meters, and the new MBCP were installed in December 2018. The mixer/aerators have typically operated at the lowest torque setting with a typical power draw of 9 kW per unit. Upper Blackstone operates with three bioreactors (six mixer/aerators) in the summer and fall months and four bioreactors (eight mixer/aerators) in the spring and winter months, resulting in an annual energy consumption of approximately 550,000 kWh/year. This incurs an annual cost of $72,000 at $0.13/kWh. Thus, the net cost savings associated with installing the mixer/aerators to decouple mixing from process aeration appears to be on the order of $186,000 per year. This net savings estimate accounts for the MicroC savings which are partially offset by the additional power consumption.

RESULTS AND DISCUSSION – BLOWER AND MOV CONTROL

“Most open valve” is a term often used but not well understood. An MOV algorithm with header pressure control was developed as far back as 1978 and was used to optimize efficiency in steam systems with a common header. It was noted that throttling is an irreversible process, and it would be desirable to force control valves further open while maintaining control of their individual variables (Cho, 1984). This is the same basic principle modern aeration control MOV systems are trying to satisfy. Jenkins (2013) notes that pressure was added as a control variable for the main system header to overcome the loop independence issues created by the inability of older controllers to share data in real time. All loops were essentially independent of each other even if there was a process relationship between them, but adding pressure allowed programmers to employ cascaded loops where the output from one control loop became the set point for another loop. This was typically done using a constant header pressure control strategy.

Jenkins (2013) explains why floating pressure-based MOV for aeration control was developed to improve upon inefficient, constant pressure set point blower control. MOV and blower controls based on proportional-integral-derivative (PID) loops with a floating pressure set point became widely adopted starting in the 2000s, and MOV control using non-PID based loops has been developed by some as an alternative to PID systems. Additionally, some have touted Flow MOV blower control as an enhancement on Pressure MOV. Gray and Kestel (2013) used model simulations to compare different control systems and concluded that flow-based blower/MOV control yielded a small energy savings and also improved stability with less hunting. **Table 5** presents the potential benefits and disadvantages of Pressure MOV versus Flow MOV controls.

Table 5. MOV Programming Alternatives for Dissolved Oxygen Control

Type	Description	Advantages	Disadvantages
Pressure PID Blower Control with DO PID Loops	▪ Three cascades of PID control loops ▪ DO PID loop assumes linear relationship between airflow and DO; Linear relationship is established during system startup/tuning	▪ Well-established ▪ More widely known by system integrators ▪ Pressure transmitter provides a single, stable reading for blower control	▪ Fixed adjustment of pressure is more susceptible to oscillation/hunting in response to major system changes ▪ Increases response time of control system ▪ Re-tuning DO and pressure PIDs may be required more often for optimal performance because relationships between controlled variables change depending on ambient conditions and no. of operational blowers
Pressure Non-PID Blower Control with Floating DO Loops	▪ DO and valve control loops use a “Proportional and Pause” approach; not PIDs. For DO loop, changes in air flow required to meet DO set point are adjusted in direct proportion to the error and then system pauses before making adjustments. ▪ Blower pressure control loop uses fixed adjustments rather than proportional adjustments.	▪ Well-established ▪ Less widely known by system integrators than systems using PIDs ▪ Pressure transmitter provides a single, stable reading for blower control ▪ Minimizes oscillations since DO PID loops are not used	▪ Fixed adjustment of pressure is more susceptible to oscillation/hunting in response to major system changes ▪ Re-tuning may be required periodically for optimal performance, although likely less necessary than for PID-based ▪ May require process expertise rather than PID loop knowledge to tune
Flow Non-PID Blower Control with Floating DO Loops	▪ All control loops (DO, valves, and blowers) use a “Proportional and Pause” approach; not PIDs. For DO loop, changes in air flow required to meet DO set point are adjusted in direct proportion to the error and then system pauses before making adjustments.	▪ Blower output matches system demand ▪ Minimizes oscillations since DO PID loops are not used ▪ Might result in more stable operation and/or faster response time, particularly for systems with very long piping runs	▪ Flow signals are less stable than pressure readings, but signals can be dampened or change in flow (delta) can be used instead ▪ Re-tuning may be required periodically (seasonally) for optimal performance, although likely less necessary than for PID-based ▪ May require process expertise rather than PID loop knowledge to tune

Figure 6 presents an example of the manual valve positions at Upper Blackstone before the MBCP was installed and **Figure 7** presents the DO in individual control zones while utilizing manual valves for control. Both figures highlight why providing modulating valves for all 20 control zones is necessary when tight DO control is desired to optimize the process. The system was achieving the desired DO set points during portions of the day, but there was significant variability in response to diurnal patterns. Also, the most open valve position on the day shown in **Figure 6** is 65 percent, thus adding unnecessary pressure drop into the system. MOV programming ensures at least one valve is set to its most open position, opens the remaining valves, and reduces blower output to minimize system pressure. Prior to the upgrade, Upper Blackstone's operators adjusted the manual dropleg valve positions two to three times per shift (three shifts a day) in order to achieve the level of control demonstrated in **Figure 7**. Upper Blackstone could have hired one full time employee to adjust the valves all day long and still would not achieve the level of control offered by the upgraded MOV controls.

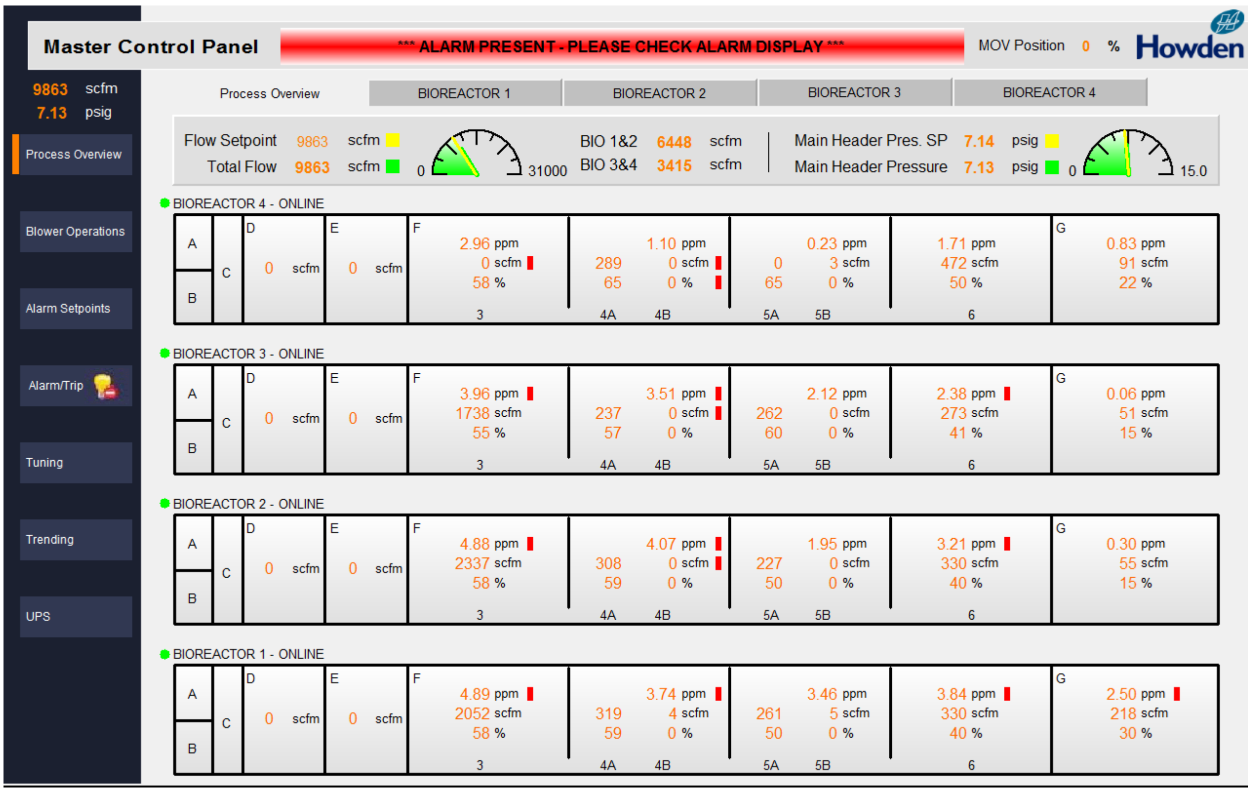

Figure 6. Valve Positions When Operating Without MOV Control Strategy

The two auto control modes employed by the master blower controls provided at Upper Blackstone are non-PID methods. As shown in **Figure 7**, there was an immediate improvement in maintaining DO set points for the control zones when the control scheme was switched to Auto MOV Flow Control in mid-December 2018.

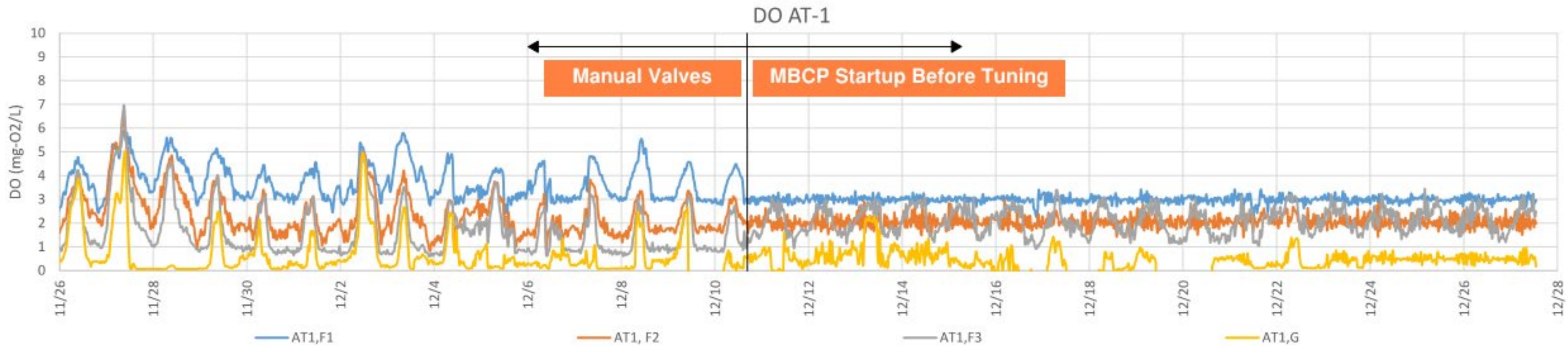

Figure 7. DO when Operating without MOV Control Compared to DO after MBCP Startup with Flow MOV Control

The upper chart in **Figure 8** demonstrates the improved level of DO control once the Auto MOV Flow Control mode was tuned. The DO concentrations in each zone are stable despite changing flow and load conditions, with tight DO bands around the set points. When there were some larger fluctuations, the system recovered quickly. The lower chart in **Figure 8** shows the airflow into specific control zones. As expected, Zone F1 at the upstream end of the aerobic zone requires the most air. During the timeframe shown, one of the two valves associated with the grid-within-a-grid zones (F2 and F3) was typically closed, indicating that the flow into those zones was below the established low flow thresholds. There are also a couple of occasions when the airflow into Zone G (with the mixer/aerators) approached zero, indicating that mostly mixing (and not aeration) was required during those timeframes.

Figure 9 shows the screen at the MBCP from which an operator can select the desired control mode. The screen indicates that the control scheme is in Auto MOV Flow Control since the status is “Auto MOV” under the Flow Control header and “Flow Control” under the Pressure Control header. Two key parameters for monitoring the performance of the auto control modes are *MOV position* (at the top right of the image) and the *Total Process Flow Error* (displayed above the Blower 2 graphic). When this screenshot was taken, the MOV position was 88% and the total error was 8 scfm. This indicates the system was working well since the MOV position is high and the flow error is low. Upper Blackstone is going to trend these parameters to monitor performance of the auto control modes. Low MOV positions and/or high flow error on a consistent basis would suggest that additional tuning is recommended.

Upper Blackstone has predominantly operated in Auto MOV Flow Control since switching to the new control scheme in December 2018. Testing of the Auto MOV Pressure Control Mode will be completed in June 2019, after which a comparison between Auto MOV Flow and Auto MOV Pressure can be made. In addition to MOV position and flow error, system pressure will be tracked to evaluate the two different auto modes. It is expected that Upper Blackstone will remain in flow-based control, but a comparison of performance will help make the ultimate determination.

An immediate drop in system pressure of approximately 1.4-1.7 kPa (0.20-0.25 psig) was noted after the switch to Auto MOV control was made in December. This delta in system pressure will be monitored for the remainder of the year to determine if the lower pressure is maintained, thereby resulting in an annual energy savings associated with the blowers.

Figure 9. Typical DO (*upper chart*) and Zone Air Flows (*lower chart*) When Operating With Flow MOV Control Strategy (Taher et al)

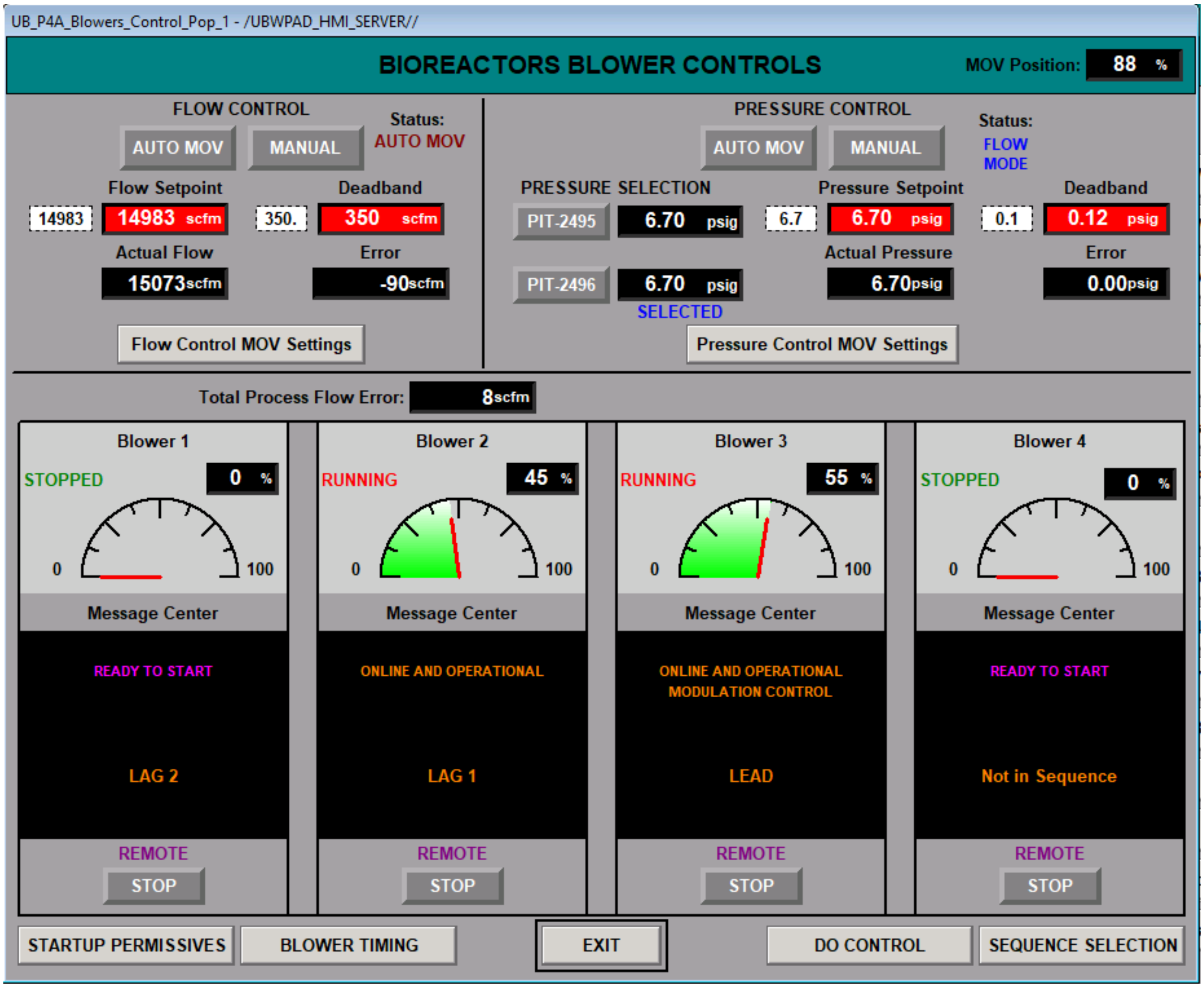

Figure 9. MBCP Control Screen During Auto MOV Flow Control

years during its permit compliance months (which are April through October for phosphorus and May through October for nitrogen). The 2010-2014 statistics represent performance before optimization measures were Listed below are some recommended best practices and some lessons learned from implementing the new aeration control scheme at Upper Blackstone and operating it for approximately six months:

- *Flow-based systems need to consider pressure as a safeguard to protect the blowers due to individual flow meter or control valve failures.* This was evidenced by a scenario during which a valve failed in a somewhat closed position but the Profibus network was showing it as open greater than the MOV limit. The airflow was low because the valve was mostly closed. The low air flow was much lower than the minimum for that zone. Therefore, this zone showed a flow error which was large enough to increase the total flow set point. As the blowers' output increased, the flow error of this zone did not change much. The total flow set point continued to increase because of this zone and the blowers continued to increase their output. The system eventually reached the pressure limit set in the MBCP which prevented the flow set point from increasing any further.

- *Since flow meters are calibrated to a specific flow range, ensure the flow meters fail to a max value and not to zero.* Originally the flow meters furnished for this project would reach their limit and then higher flow rates would results in an output of zero for flow. This caused the calculated total flow to suddenly drop, which then caused the blowers to ramp up to meet the total flow set point. As the blowers ramped up, the next flow meter would saturate and go to zero, the calculated total flow would drop, and the blowers would ramp up again. This was fixed by reprogramming the flow meters to fail to a value just above its max reading. For example, it would fail at 1201 scfm if the max flow was 1200 scfm. This prevents the run-away blower scenario described above and also alerts operators to the fact that this meter is not giving a real reading. From a design perspective, engineers could specify wider flow ranges to minimize the potential for this issue to occur.

- *Provide adequate fail-safes in the programming to ensure stable operation even during equipment fault and communication fault conditions.* This includes network communication failures or analog transmitter failures. It also includes providing the ability for operators to drop individual control zones from the control scheme due to scheduled maintenance or mechanical issues not captured by the control system. High/low alarms for DO, air flow, and valve travel (not opening/closing) are included to alert the operator to potential issues.

- *Include adequate time and multiple trips by the MBCP programmer to train facility staff on the new advanced aeration control system.* A simulation of the control scheme could also be used to allow operators to understand the impacts of making certain changes or parameter adjustments without worrying about damaging the blowers or impacting process performance. The simulator training can be conducted prior to handing the system over to the operators and then perhaps after six months of operation when the operators are more familiar with the system to ask detailed questions.

- *The higher capital cost for the iris diaphragm valves was justified for this facility due to the tight level of control needed to meet stringent nutrient limits.* Iris diaphragm valves were selected for Upper Blackstone after a life cycle cost evaluation (Doody and Neville 2017). The control range of the iris valve was a major factor in that determination and controllability between 90 to 100% open was demonstrated during testing. Controllability of butterfly valves is typically capped at 80%. The tighter control and wider range of control on both the high % open and the low % open made for a more flexible control system at Upper Blackstone and made it easier for the programmer to tune the system.

- *Iris diaphragm valves provided more stable flow readings upstream of the flow meter compared to typical systems with butterfly valves.* Flow-based MOV control systems often use a filter on the flow reading in order to stabilize feedback from flow meters since flow readings tend to fluctuate frequently. This was not required at Upper Blackstone due to the stable flow meter readings upstream of the iris diaphragm valves. The stable readings also allowed the programmer to set tighter flow dead bands on some of the control zones than if butterfly valves were utilized.

RESULTS AND DISCUSSION – EFFLUENT QUALITY

The Phase A nutrient upgrade at the Upper Blackstone facility included state-of-the art aeration controls and it made permanent several operational tools that have yielded improvements in BNR process stability, including permanent facilities for the supplemental carbon storage tanks and feed pumps. **Figures 10 and 11** demonstrate the improvement in effluent TP and TN performance Upper Blackstone has achieved over the past 8 tested, and the 2015-2018 statistics represent performance during implementation of optimization measures and construction of the Phase A upgrades. The 2018 data capture the results when the majority of the facility was operating with mixer/aerators and manually controlled iris valves.

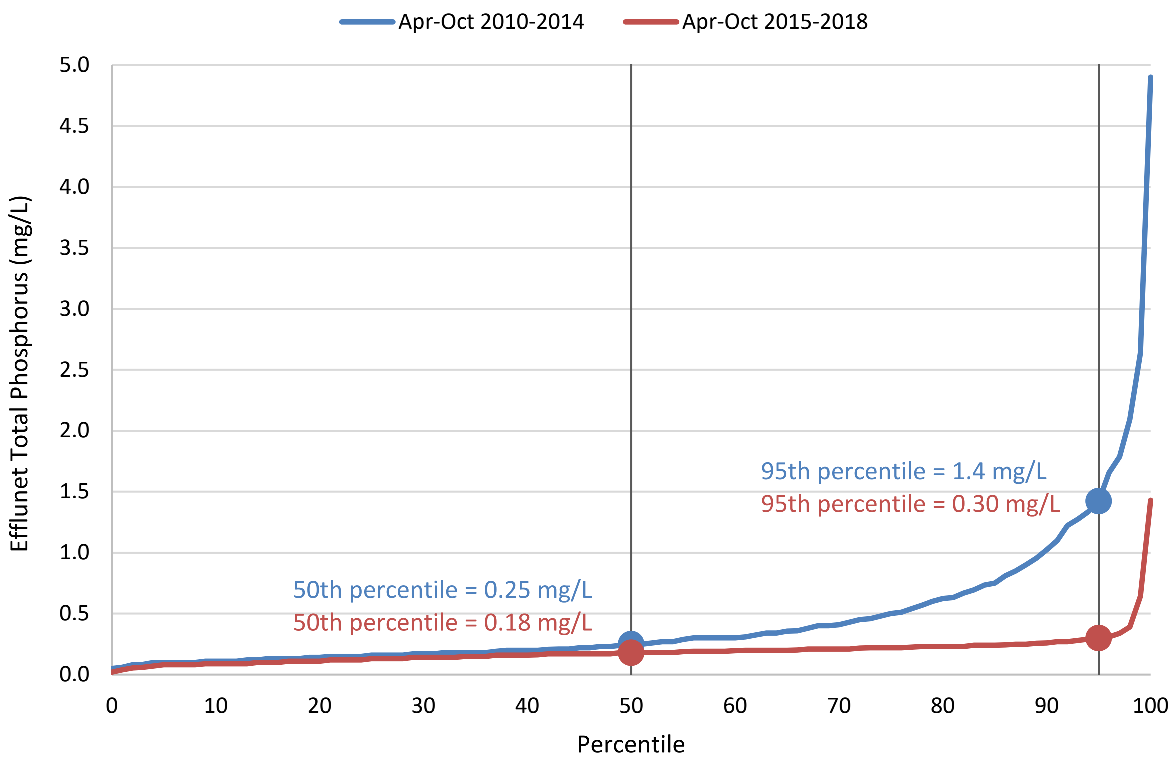

Figure 10. Effluent Total Phosphorus Pre-Optimization vs. Post-Optimization Program

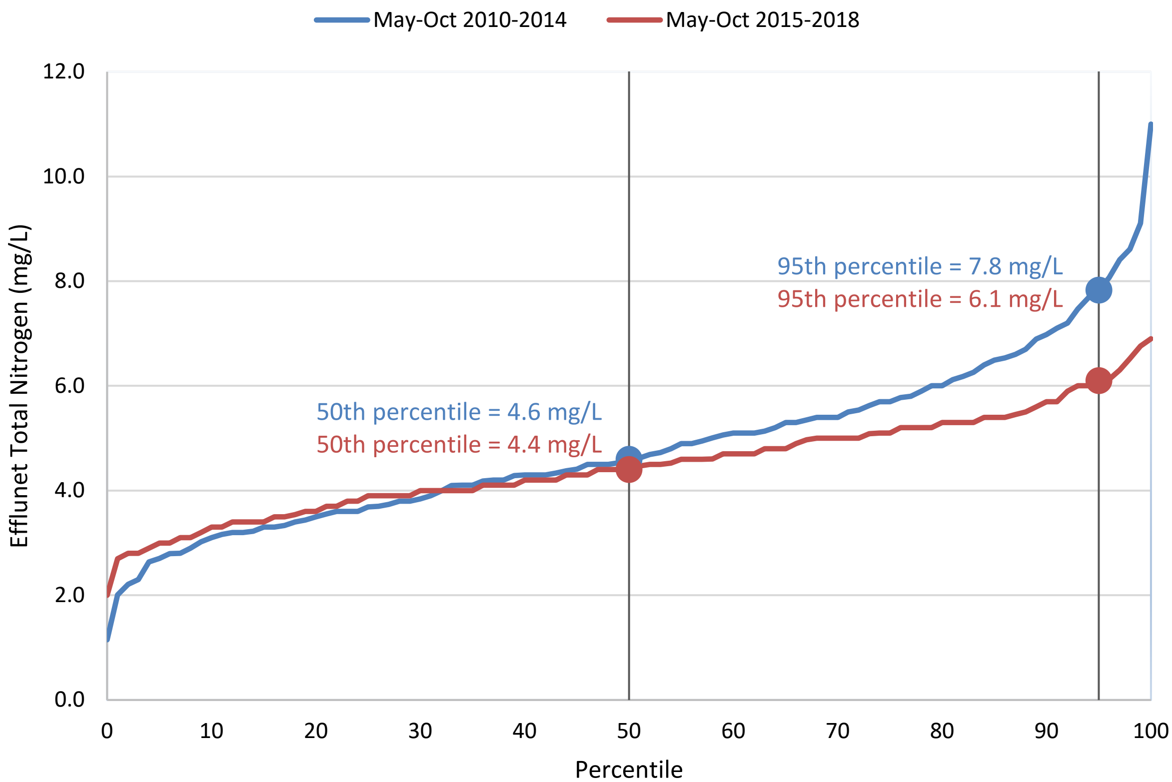

Figure 11. Effluent Total Nitrogen Pre-Optimization Versus Post-Optimization Program

Table 6 compares performance in April and May 2018 compared to April and May 2019, where the 2019 data reflect performance when Upper Blackstone has been operating with the Auto MOV Flow Control mode. TN results are not presented for April since Upper Blackstone does not have to meet the TN permit that month.

Table 6. Comparison of Performance in 2018 to 2019

Item	During Phase A Construction (Mixer/Aerators and Manual Valves)		After Phase A Commissioning (with MOV Automation)	
	April 2018	May 2018	April 2019	May 2019
Effluent TP (mg/L)	0.18	0.16	0.11	0.07
Effluent TN (mg/L)	-	4.6	-	4.6

The monthly average effluent TP concentrations for April and May 2019 were closer to 10th percentile results when compared to **Figure 10**. The range of daily concentrations in 2019 was also narrow: 0.04 to 0.24 mg/L for April and 0.02 to 0.12 mg/L for May. The monthly average effluent TN concentration for May 2019 was the same as 2018 and both were about a 55th

percentile value when compared to **Figure 11**. The TN range for May 2019 was also narrow at 4.0 to 5.2 mg/L. These results demonstrate that the recent aeration system upgrades are allowing Upper Blackstone to maintain good EBNR performance with the A^2/O process, but at a lower cost compared to prior years.

CONCLUSIONS

Upper Blackstone implemented new advanced aeration DO controls that were started up in December 2018. A main driver for the upgrade was to improve DO set point control tapered down the length of the bioreactors, which is Upper Blackstone's preferred mode of operation for its A^2/O EBNR process. The new MOV control scheme has demonstrated tighter control of the DO set points with significantly less operator intervention. The combination of the MOV upgrades (which provide tighter DO control) and the installation of mixer/aerators (to decouple mixing and aeration at the effluent end of the bioreactor) has resulted in a significant reduction (greater than 50%) in supplemental carbon addition due to the reduction in DO recycled to the anoxic zones. The effluent nitrogen concentrations have remained similar compared to previous years with the lower carbon usage.

Upper Blackstone has four control modes they can select from at the MBCP: (1) Auto MOV Flow Control, (2) Auto MOV Pressure Control, (3) Manual Flow Control, and (4) Manual Pressure Control. The control system has predominantly been operated in Auto MOV Flow Control since December 2018 and it has provided stable blower operation and DO control, as well as a reduction in system operating pressure. The Auto MOV Pressure Control mode will be tested this month and will be compared to flow control based on MOV position, total system flow error and system pressure.

There was significant capital cost associated with the recent upgrade, but the initial results indicate Upper Blackstone will save on both chemical and energy costs while maintaining the high performance of the A^2/O process. In addition, the process performance results are being achieved with significantly less operator intervention compared to the prior manual operation.

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