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EXPANSION AND UPGRADING OF COLUMBUS, OH WWTPs TO ADVANCED WASTEWATER TREATMENT

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ABSTRACT

In December 1985, the City of Columbus, OH initiated a $220 million program for upgrading capacity and treatment from secondary to advanced wastewater treatment (AWT). The two plants (4990 L/s and 2630 L/s) were required to be fully operational by July 1988. The existing plants had a history of bulking sludges and it was necessary that design/construction proceed concurrently with a laboratory 18-month sequencing batch reactor (SBR) study to evaluate bulking sludge control while producing the required effluent quality of $CBOD_5$, TSS and NH_4N of 8, 16 and 1 mg/L, respectively. Completion was on schedule and full-scale results paralleled those produced by the SBR sludge. Average effluent concentrations from the larger plant for the 2.5 years of operation were 2 mg/L $CBOD_5$, 5.5 mg/L TSS, 1.5 mg/L TKN, 0.13 mg/L NH_4N and 1.1 mg/L TP. The problems resulting from unexpectedly high sludge yields and inadequate sludge transport capacity in the 61 mϕ clarifiers are discussed and resolutions presented.

KEY WORDS

Semi-aerobic selectors, nitrification, sludge yield, SBR modeling, sludge collection, sludge transport, scraper design, advanced wastewater treatment.

BACKGROUND

Columbus, the state capital of Ohio, is a major commercial and industrial center located in the geographic center of the state. The climate is characterized as humid continental, with a January and July mean temperature of 0°C and 25°C, respectively. Rainfall is fairly well distributed throughout the year with the mean annual precipitation averaging 96.5 cm.

Columbus is located on the Scioto River, a tributary of the Ohio River originating in northwestern Ohio and flowing 217 km southeast to the Ohio River. The Scioto River at low flow in the Columbus area is characterized as a small pool and riffle stream with much of the slope gradient in the range of 0.32 m/km. Approximately 65% of the population in the Scioto River basin live in the Columbus area. Several water supply, flood control and reaeration impoundments have been constructed on the Scioto River and its major tributaries, altering the flow characteristics.

Columbus operates two major wastewater treatment facilities. The Jackson Pike Wastewater Treatment Plant (WWTP) in southwest Columbus was constructed in the late 1930s with a hydraulic capacity of 4030 L/s. It was modified in 1988 and currently has an AWT capacity of 2630 L/s. The Southerly WWTP is located 13.7 km south of downtown Columbus. Southerly was constructed in 1967 for 4380 L/s, expanded to AWT in 1988, and now provides a capacity of 4990 L/s. The plants serve a population of 872,000, including twenty adjacent small communities besides the City of Columbus as well as some major industries. The plants are inter-connected by a 3.9 m diameter sewer to transfer flow from the larger Jackson Pike service area to Southerly.

During dry weather and low river flow periods, effluent discharged to the Scioto River from both plants has a significant impact on the water quality of the receiving stream. Columbus is authorized, by a 1913 statute, to divert all upstream flows of the Scioto River for the purpose of maintaining the public water supply. This authority has resulted in an occasional "no flow" condition at the Dublin Dam water intake. The only assured water sources during low flow periods are a guaranteed 140 L/s flow from an upstream reservoir located on a major tributary and the City's two treatment plants. Jackson Pike WWTP routinely contributes as much as 95% of the extreme low flow discharge in the river stretch between the two plants.

The regulatory agency designated the reach of the Scioto River receiving the effluent from the treatment plants as capable of supporting warmwater habitat. The agency also issued use designations of agricultural water supply, industrial water supply, and primary contact recreation.

The original effluent permit values of 5 mg/L $CBOD_5$, 10 mg/L TSS and 1.5 mg/L NH_4N were renegotiated to yield about the same ultimate or total oxygen demand (TOD) value, with $CBOD_5$, TSS and NH_4N limitations of 8, 16 and 1.0 mg/L. This change resulted in the elimination of effluent sand filters at a savings of $50,000,000 to Columbus.

DESCRIPTION OF PLANT FACILITIES AND LOADINGS

The Jackson Pike and Southerly WWTPs, prior to the modification/expansion, were of similar design: conventional pretreatment, pre-aeration, rectangular primary clarification, two-pass plug flow or step feed aeration basins, and rectangular final clarifiers. Sludge disposal was provided by centrifugal dewatering and combustion or land disposal. The major wet processing elements before and after the 1988 expansion are provided in Table 1.

Jackson Pike aeration basins were retrofitted with fine bubble membrane diffusers, improved aeration tank baffling and minor modifications in down-rating the secondary treatment capacity to 2630 L/s in an AWT mode. The Southerly plant was also retrofitted with tubular membrane diffusers and expanded with new facilities to bring the flow capacity to 4990 L/s. The influent design loadings for each facility are set forth in Table 2.

TABLE 1. JACKSON PIKE AND SOUTHERLY WET PROCESS FACILITIES

Plant	Existing	New
Jackson Pike		
Primary Clarifiers	8-45.7 m x 24.4 m x 3.05 m	—
Aeration Basins	10-274 m x 7.92 m x 4.57 m	—
Final Clarifiers	12-45.7 m x 24.4 m x 3.81 m	—
Southerly		
Primary Clarifiers	4-51.8 m x 24.4 m x 4.57 m 4-51.8 m x 24.4 m x 3.05 m	2-54.9 mϕ x 4.57 m
Aeration Basins	10-274 m x 7.92 m x 4.57 m	6-274 m x 7.92 m x 4.57 m
Final Clarifiers	Demolished in 1988	6-61 mϕ x 4.57 m

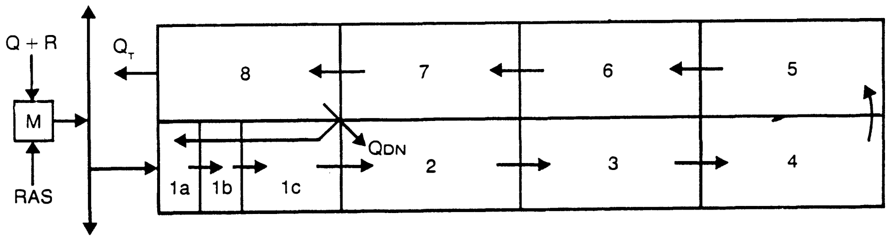
TABLE 2. INFLUENT DESIGN LOADINGS - YEAR 2008

	Q L/s	BOD_5 kg/d	TSS kg/d	TKN kg/d	TP kg/d
Jackson Pike	2,630	42,450	53,870	5,870	1,826
Southerly	4,990	84,700	85,140	10,800	3,457
Total	7,620	127,150	139,010	16,670	5,283

The process design for the facilities was influenced by the need to control bulking sludge. A large brewery contributed a significant portion of the organic wastes to Southerly and there was a history of severe bulking incidents. The process selection and design precluded pre-design pilot studies due to the construction schedule. The selector process design employed was called Semi-Aerobic in that it featured either aeration, nitrate recycle or both in the initial contact zone of return sludge and primary effluent. The Jackson Pike design employed the aerated low D.O.-high F/M selector design described by Kroiss (1985), Albertson (1987) and Chudoba and Wanner (1988). Chudoba's studies (1973,1974) and Tomlinson's (1979) review of English biological facilities have previously demonstrated the value of aerated compartmentalization to control filamentous growth or bulking sludges.

SELECTOR/AERATOR DESIGNS

The Southerly 274 m long basins were baffled to provide three selector zones producing a Σ F/M gradient of 5.5, 2.8 and 1.4 kg/kg MLSS·d at design loadings. The basins were thereafter baffled into seven additional aeration zones of equal size as shown in Figure 1. Zone Bays 1a, 1b, 1c and 2 were equipped with jet aeration. While the selectors could operate in a low D.O. (0.0-0.3 mg/L) mode only, Bay 2 was designed to operate either as fully oxic or anoxic by remote control of the air rate to the jet aeration. Membrane diffusers were installed in Bays 3-8.



COMPARTMENT	MODE	ENVIRONMENT	EQUIPMENT
1a	MIX/AERATE	ANOXIC	JET AERATORS
1b & 1c	MIX/AERATE	ANAEROBIC/ANOXIC	JET AERATORS
2	MIX/AERATE	ANAEROBIC/ANOXIC/OXIC	JET AERATORS
3 - 8	AERATE	OXIC	FB DIFFUSERS

Fig. 1. The Columbus Semi-Aerobic Process Arangement

The Semi-Aerobic reactor designs differ slightly in the two plants. For an interim modification at Jackson Pike, there are only two selector zones since the $SBOD_5/TBOD_5$ is only 0.25-0.30 in the primary effluent. The $SBOD_5/TBOD_5$ ratio at the Southerly plant with the brewery load is 0.65-0.75. An internal recycle flow at Southerly was designed to produce a TN less than 10 mg/L. The design criteria and operating conditions are set forth in Table 3.

TABLE 3. AERATION DESIGN CRITERIA AND OPERATING FACTORS

	Jackson Pike		Southerly	
	Design	Actual[(1)]	Design	Actual[(1)]
Flow - L/s	2,630	2,590	4,990	4,510
BOD_5 - kg/d[(2)]	30,560	19,100	60,230	38,270
TKN - kg/d[(2)]	5,280	4,270	9,720	8,470
MLSS - mg/L	2,500	1,377	3,500	3,165
SRT - days	8.6	13.9	8.7	13.8
SVI - mL/g	—	71	—	80

[(1)] July 88 - Dec 90 averages.

[(2)] 80th percentile loadings, 50th PC ≈ 85% of values shown.

FINAL CLARIFIER DESIGN AND OPERATION

The existing final clarifiers at Jackson Pike were retained and upgraded. Effluent launder covers were added to control algal growth. The six new 61 mϕ clarifiers at Southerly featured dual floor slope, 22.9 mϕ paddle flocculating feedwells and spiral scrapers on two full arms and 50% diameter stub arms. The scraper blades were 0.28 m deep and rotated at 3.03 m/min at the periphery. The centrally driven paddle flocculators operated at 0.15 - 0.60 m/s. A 1.2 m wide Stamford baffle (Semon, 1982) and a covered single overflow weir at the wall were provided to prevent upwelling currents at the wall. The design and operating conditions for the final clarifiers are set forth in Table 4.

TABLE 4. CLARIFIER DESIGN AND OPERATING CONDITIONS - SOUTHERLY

	Design			Operating		
	AA	MM	PD	AA	MM	PD
Flow - m^3/s	4.99	5.73	6.57	4.51	5.73	7.49
Overflow Rate - m/hr	1.03	1.18	1.35	0.93	1.18	1.55
Detention Time - hrs	4.5	3.9	3.4	4.9	3.9	3.00
Weir Rate - $m^3/m \cdot hr$	15.6	18.0	20.6	14.1	18.0	23.5
S.L. Rate - $kg/m^2 \cdot hr$	5.7	6.6	7.3	4.1	5.7	4.9
Return Sludge - g/L	9.40	9.20	9.00	11.36	11.90	11.28

AA = annual average, MM = maximum month, PD = peak day.

During the startup of the final clarifiers, SVIs of 130-150 mL/g resulted in sludge blankets within 1-2 meters of the surface at a solids loading rate (SLR) of 4.1-4.9 $kg/m^2 \cdot hr$. Further, as shown in Figure 2, the sludge blanket increases as a function of the RAS/Q, similar to that described by Günthert (1985) and Albertson and Okey (1990). Dye studies revealed that the rise in the sludge blanket reflected increased short-circuiting to the underflow prompted by higher return sludge ratios. Figure 2 also showed that the feedwell was too deep, causing scour at the blanket and a boil of solids outside the feedwell.

Results of the dye studies showed that the wall-to-hopper sludge transport time was 4-5 hours. A sludge transport calculation using f = 0.2 (80% slippage and short-circuiting) also produced 4.5-5.0 hours of transport time. The analysis concluded that the combination of shallow scrapers and a 3 m/min tip speed was unable to provide the required sludge transport capacity.

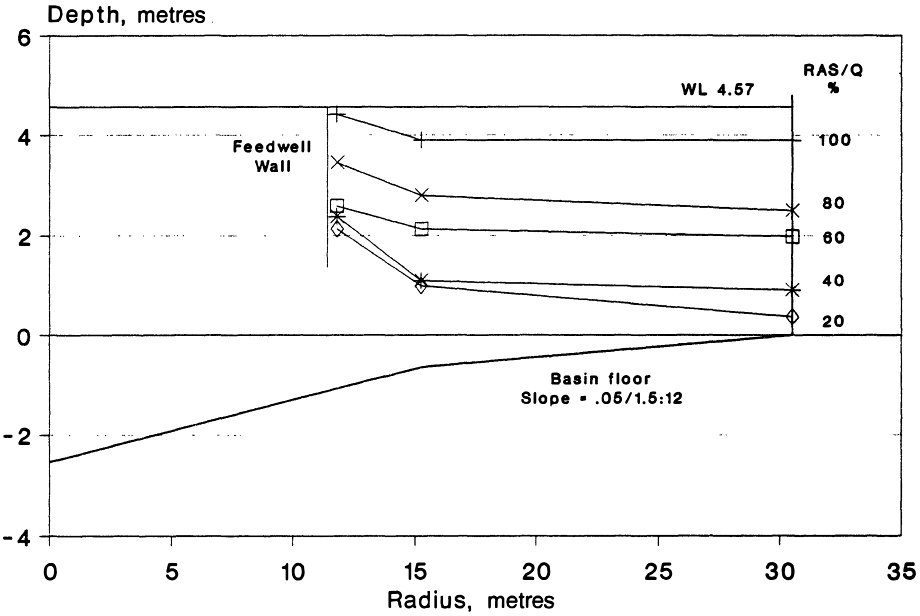


Figure 2. Elevation of Blanket Surface vs RAS/Q Ratio

The startup of the low D.O.-anoxic selectors resulted in a sharp drop in the SVI to 60-90 mL/g and a corresponding increase in RAS concentration. As expected, the sludge blankets subsided as the reduced underflow volume approached the conveyor transport capacity. The existing 280 mm scrapers are not adequate to transport the sludge volume produced at design loadings and at an SVI of > 80-90 mL/g.

The two new 61 mϕ x 4.57 m side wall depth (SWD) clarifiers now under construction will have an improved scraper design employing tapered spiral blades of 0.30 m to 0.95 m in depth and two-speed drives for 3 m/min and 4.6 m/min. Normal operation will be at the lower speed and the higher speed employed if the blankets increase at maximum loadings or higher SVIs. These two additional units will increase the peak hydraulic capacity at Southerly to more than 9000 L/s and reduce the SLR on the clarifiers by 33%, easing transport problems.

PILOT PLANT EXPERIENCES

The process design for Southerly used a high MLSS of 3500 mg/L and initially the first six of eight clarifiers would have a high solids loading. Since Southerly had a history of bulking, successful operation was dependent on the capability of the selectors to control bulking.

The decision was made to use laboratory SBRs to model the planned compartmentalized selector/aeration basin. In a nitrifying mode, the initial contact of influent and return sludge in an SBR is anoxic as in the new plant design. In the SBR, time is the baffle and in the full-scale, flow-through basin, baffles can be added as required to separate biological functions and optimize kinetic rates.

While it was necessary to complete engineering and start construction before any meaningful pilot data could be collected, laboratory studies were initiated and conducted over an 18-month period. The laboratory studies used two 8 L SBRs operating simultaneously at low winter and average summer temperatures. The studies were necessary due to the low design solids retention times (SRTs) as well as known nitrification inhibition in the Southerly wastewater. A total of 11 individual studies were conducted at winter and summer water temperatures and SRTs from 7-12 days.

The initial studies quickly determined the existence of high sludge yields, which would result in a much lower SRT than the original design basis of 12 days at 12 °C. In order to determine if the existing design was operable, the SRT was reduced to nine days and then to seven days to evaluate the range of full-scale operation. Since the Southerly plant would receive flow from the Jackson Pike service area, tests were conducted using a mixture of the two wastewaters.

Although some data were not available until the end of the construction phase, the results of the 1 1/2-year SBR studies still provided insights to the wastewater treatment capabilities. Specifically,

1. Excess sludge production was 0.85-0.95 kg/kg BOD_5 removed.
2. Nitrification toxicity was both chronic and acute in the Southerly service area.
3. SBR data were used to position and add baffles to control back-mixing.
4. Oxygen utilization profiles and denitrification and nitrification rates were established.
5. While the Southerly nitrification rates were 25-35% of Jackson Pike rates, the mixture was synergistic in that the resulting rate was much higher than the weighted average.
6. An excellent profile of the characteristics of the Southerly primary effluent was produced.

The testing basis and average results are shown in Table 5. Most importantly, the tests indicated that the existing design, while using a plant-scale SRT less than standard practice, would produce the required effluent quality and provide control of the SVI. The data are presented later in a comparison to the plant effluent quality. The effluent quality was poorer at a 7-day SRT.

TABLE 5. DESCRIPTION AND RESULTS OF SBR TEST PHASES.

Phase	Temp °C	SRT_{OX} Days	Average Effluent Quality - mg/L					SVI mL/g
			$CBOD_5$	TSS	TKN	NH_4N	TP	
I	12	12	1.5	2.9	1.2	<0.2	0.1	83
II	12	9	2.0	3.7	1.4	<0.2	0.1	89
III	15	9	2.0	3.6	1.2	<0.2	0.2	101
IV A	12	9	3.0	5.5	1.3	<0.2	0.5	94
IV B	21	9	4.1	9.9	1.8	<0.2	3.1	77
V A	12	9	2.6	9.2	1.6	<0.2	3.5	99
V B	21	9	2.0	4.9	1.4	<0.2	3.3	79
VI A-1	12	7	3.9	11.4	2.1	<0.2	4.3	86
VI B-1	21	7	4.0	9.8	2.0	<0.2	5.1	84
VI A-2	12	7	3.0	10.0	2.0	0.2	2.9	87
VI B-2	21	7	4.0	15.6	2.5	<0.2	4.3	70

Full-scale, pre-startup studies were also conducted at Southerly (Contract 20) and Jackson Pike. These studies provided further confirmation of the design as well as emphasized the need to control the introduction of toxic substances into Southerly. Later results demonstrated that these acute discharges were eliminated or at least controlled to eliminate acute toxicity.

PLANT EFFLUENT QUALITY

The two Columbus plants have produced a stable effluent quality well within the permit criteria. The facilities have not reached design organic loadings but have successfully operated in excess of the design hydraulic requirements. The 2 1/2-year performances of the Jackson Pike and Southerly facilities are shown in Table 6.

The small differences between the average monthly and the 80th percentile effluent values reflect the stability of the Semi-Aerobic system. Phosphorus removal at Jackson Pike is much lower, as anticipated, due to the low $SBOD_5/TBOD_5$ in the aeration influent. Phosphorus removal was not a requirement, thus there is no optimization of the operation for TP removal in either plant.

TABLE 6. AVERAGE AND 80TH PERCENTILE EFFLUENT QUALITY

Effluent Parameter	Jackson Pike Avg	Jackson Pike 80th PC	Southerly Avg	Southerly 80th PC
$CBOD_5$ - mg/L	3.3	4.0	2.0	2.0
TSS - mg/L	8.5	10.0	5.5	7.0
TKN - mg/L	1.6	1.7	1.5	1.7
NH_4N - mg/L	0.11	0.12	0.13	0.18
TP - mg/L	3.6	4.1	1.1	2.0

The Southerly effluent quality is the equivalent of a total oxygen demand (TOD) of 1.5(2 mg/L BOD_5) + 4.6(0.13) or 3.6 mg/L vs the permit equivalent level of 16.6 mg/L. Jackson Pike produced an average effluent TOD of 5.5 mg/L. Both plant performances were achieved without the need for sand filtration. There are only minor differences in summer and winter performances.

COMPARISON OF PILOT TESTS AND PLANT-SCALE OPERATION

The pilot-scale and long-term operational results provide an opportunity to evaluate the feasibility of using small SBRs to model large, compartmentalized selector-aerator basins. The data can best be analyzed by comparing the average and 80th percentile data as shown in Table 7.

TABLE 7. SBR, CONTRACT 20 AND PLANT-SCALE PERFORMANCE AT SOUTHERLY

	SBR(1) Avg	SBR(1) 80th PC	Contract 20 Avg	Contract 20 80th PC	Plant Avg	Plant 80th PC
$CBOD_5$ - mg/L	2.3	2.9	2.2	3.0	2.0	2.0
TSS - mg/L	7.1	9.2	5.5	9.0	5.5	7.0
TKN - mg/L	1.5	1.7	NR	NR	1.5	1.7
NH_4N - mg/L	<0.2	<0.2	0.3	1.7(2)	0.13	0.18
TP - mg/L	3.4	4.1	NR	NR	1.1	2.0
SVI - mg/L	96	101	94	102	77	90

(1) Avg of 12 and 21 °C data @ 9 day SRT @ 2/3 So + 1/3 JP wastewater
(2) Several toxicity occurrences caused NH_4N > 10 mg/L during 4 month test.

The SBR and the plant results were remarkably similar except for TP removals. Since the SBR did vary widely in TP removal, it is possible that changes in the influent characteristics produced better results in plant-scale operation. While the full-scale studies (Contract 20) had toxicity problems, there was only a minor effect on SBR effluent quality. The reason may have been a slug loading which was equalized in the composite feed to the SBR. The full-scale, pre-startup operation (January-July 1988) is not reported here, but was equally successful.

DISCUSSION

The SBR study approach has much to offer when the full-scale design will be compartments in series. The SBR is an ideal plug flow reactor (no backmixing) and therefore, the various reactions and their rates can be established. By properly setting up fill-volume rates, internal recycle is simulated to establish an anoxic-oxic flowsheet.

The SBR also provides the opportunity to gather precise data sludge yields, oxygen consumption profiles, total oxygen quantity and effluent quality. Potential drawbacks are constant loading and a composite feed. A varying cycle time could be imposed, but this appears unnecessary and feeding a new sample every cycle requires excessive levels of wastewater feed analyses.

In hindsight, the clarifier transport problems were predictable. The scraper mechanisms were suitable for a 15-20 mϕ unit, but not one with 10-15 times the surface area, hence proportionally higher sludge quantity to transport. However, the problem can be easily corrected by scraper modifications and increased operating speed. Also, the feedwell depth of the new units will be shortened 0.67 m to reduce scour and the existing units should be modified.

SUMMARY AND CONCLUSIONS

1. The nigh to low F/M gradient selectors operating in an aerated, low D.O. and/or anoxic mode provide excellent control of bulking organisms.
2. The selector-aerator operation can be effectively modeled in an SBR if the full-scale unit is compartmentalized to isolate key reaction zones.
3. The SBR will also provide other data such as SVIs, sludge yields, oxygen profiles and quantities, toxicity indications and the kinetic rates necessary to design full-scale facilities.
4. Southerly's effluent quality is 2 mg/L BOD_5, 5.5 mg/L TSS, 1.5 mg/L TKN, 0.13 mg/L NH_4N, and 1.1 mg/L TP resulting in a TOD of 3.6 mg/L. Jackson Pike produced a TOD of 5.5 mg/L. The TOD of the effluent permit for both plants is 16.6 mg/L.
5. Currently, equipment suppliers provide inadequate scraper capacity for clarifiers over 20 to 25 mϕ at SLRs of ≥ 4 kg/m^2·hr or the equivalent return sludge rate. Longer, deeper blades are required at higher speeds.

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