# Logan Martin Dam, Alabama, Speece Cone Oxygenation

Logan Martin Dam, owned and operated by Alabama Power Co., is located on the Coosa River and was constructed on a karst stone geological foundation, 60 feet deep near the dam. The river flows 35 miles downstream past a paper mill, with less than 4 mg/L of D.O. on the weekends due to hydropower turbine shut down. Since it is operated as a peaking power dam, water is only released through the turbines between 9 a.m. and 10 p.m. on weekdays, causing approximately 900 cfs of water to leak out through the conduits in the karst foundation, in spite of extensive grouting to prevent it.

These conduits in the rock below the dam are somewhat similar to biological trickling filters in that a biological slime develops on the surface of these conduits. Consequently, even though the water contains about 8 mg/L of D.O. in the reservoir behind the dam, by the time the water leaks through these conduits beneath the dam, essentially all of the D.O. is removed. Then on weekends when water is not released to the hydropower turbines, the only water passing into the tail water zone is comprised of this 900 ft.³ per second of leakage water, which contains essentially zero D.O..

The resident fishery in the tail water below the dam is noticeably stressed during these weekend periods of low D.O. Fish by the dozens can be seen standing on their tails gulping air in an attempt to compensate for the low D.O. in the tail water. By Monday when the water now containing less than 1 mg/L of D.O., slowly passes the paper mill discharge point, the mill must curtail operation until the D.O. level again reaches about 4 mg/L.

In 1990 a Speece Cone oxygenation system was installed to meet one third of the 18,000 pound per day of oxygen required to raise the D.O. in the leakage flow to the required level. The 21 ft.³ per second system also incorporated into the final design an additional system capable of handling another 42 ft.³ per second.

This oxygenation system receives 21 ft.³ per second of water from a pipe connected to the pool above the dam. The Speece Cone oxygenation system was installed at the base in the dam so that the water from above the dam passes through the
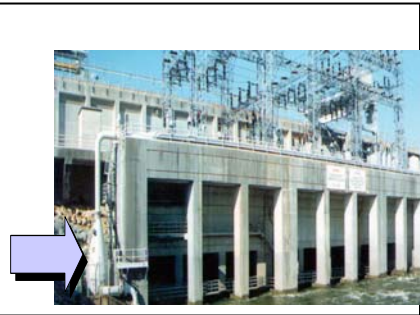
Speece Cone oxygenator and discharges about 30 foot below the tail water surface. A throttling valve is located at the discharge in the tail water to allow pressurization of the oxygenation system. This pressure corresponds to the difference in water elevation between the upstream pool and the tail water.

The water pressure in the Speece Cone is advantageous because it allows oxygen transfer to take place at a pressure of 50 foot of hydrostatic head above ambient pressure. Consequently, the discharge D.O. has a concentration of approximately 50 mg/L. Approximately 5000 pounds of D.O. is added to the tail water each day by this supplemental oxygenation system. There is a D.O. rich zone in the vicinity of the Speece

Cone discharge into the tail water of Logan Martin Dam which can provide a respite for fish when the bulk of the tail water is very low in D.O.

The performance characteristics of the Logan Martin Dam oxygenation system have been thoroughly evaluated. When the water throughput is at the design level, over 90% oxygen absorption efficiency is realized within the Speece Cone. Maximum oxygen absorption efficiency occurs at a water flow rate of 21 to 25 ft.³ per second through the system. A slight reduction of oxygen absorption efficiency occurs below this range and a more rapid decline at higher velocities.

The pressure at the oxygenation discharge with no flow through the system is 52 feet, reflecting the static head of water above the dam with respect to the location of the oxygenation cone. With no oxygen injection the discharge pressure registers 44 and 42 feet at water flows of 22 and 25 ft.³ per second, respectively and an oxygen to water injection rate of 4% results in discharge pressures of 38 and 37 feet. It is to be noted that the total head loss across the oxygenation cone is nearly constant at 6.2 feet regardless of water flow through the system when oxygen is subjected at 4% oxygen water ratio.

At the design flow of 21 ft.³ per second and 4% oxygen water ratio, the system added 48 mg/L of D.O. to a background influent D.O. of 3.6 mg/L for a total of 5600 pounds of D.O. per day or 9 pounds of D.O. per cubic feet of reactor per day, which is 100 mg/L per minute at 90% oxygen absorption efficiency. The average pressure in the Speece Cone is approximately 29 feet at the centerline of the cone and the water temperature is 86°F. At this pressure and temperature the saturation D.O. concentration would be 66 mg/L, if the gas phase is 100% oxygen. The discharge D.O. was 51 mg/L and the oxygen content of the bubbles within the oxygenation cone was approximately 83% as measured and with a 4% oxygen to water injection rate, indicating the oxygenation system is able to achieve 94% of theoretical saturation under these conditions. These results are indicative of an excellent oxygen transfer system since the hydraulic retention time is only about 30 seconds.

In the flow range of 22 to 25 ft.³ per second with an oxygen ejection ratio of 3%, the discharge D.O. was 42 mg/L for a net increase of 38 mg/L over the background level. Under these conditions, the absorption efficiency was 95%.

The Logan Martin Dam with its full-scale application of Speece Cone technology has been in operation for over 10 years.

Emscher River, Germany, UNOX Oxygenation

Located in the Ruhr District of Germany, and a tributary of the Rhine, the Emscher River receives untreated and mechanically treated wastewater from a catchment area of 768 square kilometers. Industrial loading, mainly from chemical and food industries, makes up about 50% of the organic pollution. Up to 80% of the river flow is wastewater during dry weather conditions. (Bjerre, Jacobson, Teichgraber and te Heesen 1995).

At one point along the Emscher the river is diverted through primary clarifiers and farther along it enters a biological treatment plant for removal of dissolved and colloidal organic matter and phosphorus precipitation, before discharge into the Rhine. However hydrogen sulfide problems in transit are an indirect effect of anaerobic processes occurring in the river. An oxygenation station is being used to remediate foul odors experienced by populations living near the river.

The attached photos show the channelized Emscher River. Note the concrete structure, which is similar in concept to the UNOX pure oxygen transfer system with baffles at the beginning and end to enclose a headspace for oxygen enriched gas to be trapped above the river level.

Surface aerators splash the river water in contact with the enriched oxygen to achieve elevated D.O. concentrations so as to avoid odor generation before the water enters a 10 km stretch before reaching the secondary wastewater treatment plant. Dry season flows into the treatment works inlet vary from 9 to 13 m³ per second, and the detention time is approximately 2 days.

The oxygenation system raises the D.O. in the entire river about 15 mg/L and supplements about 30,000 pounds of D.O. per day to the river.

Halwillersee Lake, Switzerland, Tanytarsus Oxygenation

In 1986, a tanytarsus diffuser system was installed in a medium-size lake in the Swiss plateau, which had experienced anoxia for a century. Lake Halwiler was eutrophic, due to excessive phosphorus loading characteristics of lakes and reservoirs in Switzerland and required deepwater oxygen bubble plume injection to prevent intrusion of hypolimnion water into the thermocline. As described by McInnis, Lorke, Wuest, Stockli and Little 2004, this system can be switched between artificial mixing using coarse air bubbles and hypolimnion lake oxygenation using fine oxygen bubbles. The six diffuser racks are 6 1/2 meters in diameter and are in a 300 m diameter circular configuration near the center of the lake.

The accompanying figures show the whole lake contour plots of typical oxygen distributions with the plume operating with pure oxygen. Of particular note is the observation that this free bubble rise system is unable to oxygenate below the diffuser system. This results in great areas of the sediment water interface, which remain anaerobic even though the water column higher in the hypolimnion is well oxygenated.

Figure 3. One of the six 6.5-m diameter Tanytarsus diffusers.

Patrick Henry Reservoir, Tennessee, Ceramic Diffusers

Liquid oxygen and ceramic diffusers, mounted on frames supported by columns anchored on the reservoir bottom, were installed from 1973 to 1976 as a pilot demonstration study (Fain 1978), following Ruane and Vigander's 1972 research on reservoir diffuser systems for hydropower sites for the Tennessee Valley Authority in Tennessee.

Later, following laboratory tests and comparison of diffuser equipment prices, a standard alumina tube with pore sizes of 15 to 20 µ was chosen to be installed on frames about 8 feet above the bottom. Transfer
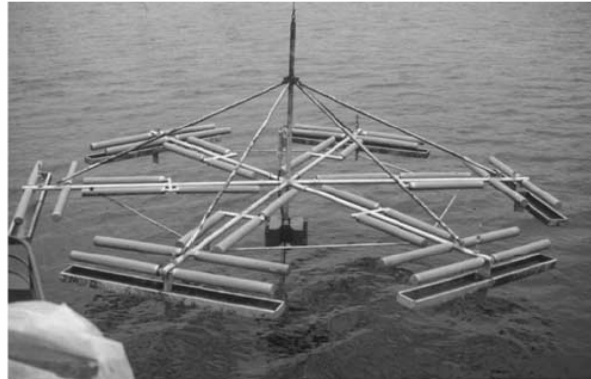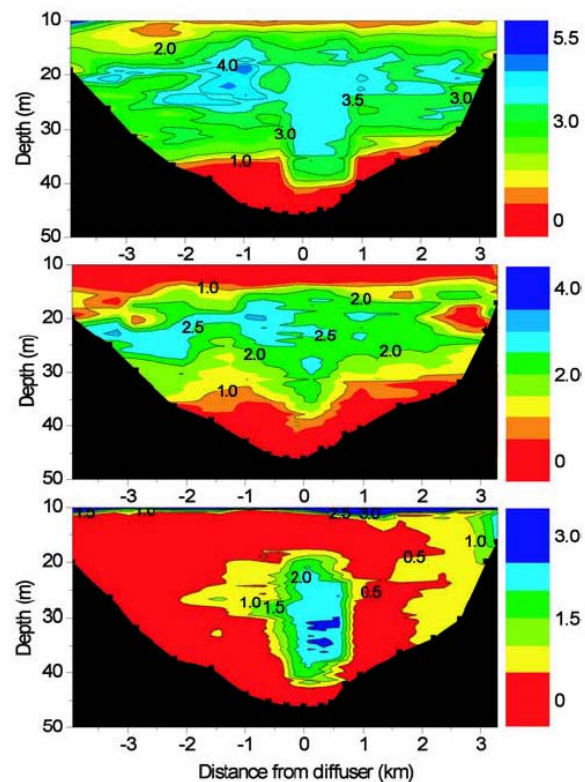

Figure 8. The (top) 24 July, (middle) 16 August, and (bottom) 27 September 2001 DO contours (g m^{-3}). Note different scales. The x axis zero point is located at the center of the 300-m-diameter diffuser ring. The contours were interpolated from 18 CTD profiles (locations indicated by black squares at the bottom of the plots) sampled along the centerline of the lake (see Figure 2 map showing 18 sampling stations).

efficiencies were not as high - 30 to 90%, as had been recorded in laboratory tests -- 80 to 90%. However smaller pore size diffusers were found to achieve higher transfer rate (Ruane, Vigander and Nicholas, Journal of Hydraulics Division of the American Society of Civil Engineers, October 1977.

Douglas Dam, TVA, Membrane and Soaker Hose Diffusers

An early hydropower installation using a membrane diffuser was chosen for Douglas Dam in 1988 by the Tennessee Valley Authority. A 20 foot by 33 for diffuser frame was placed on adjustable legs to fit the bottom topography in front of one of the intakes. Oxygen transfer efficiencies of about 72% were measured late in the D.O. season of 1988, when weak stratification conditions existed (Mobley, 1989). D.O. improvements in the releases were about 2 milligram per liter. However, during the peak of the 1989 D.O. season, the oxygen improvement in the releases dropped to nearly 0 mg/L. This was attributed to oxygen demand stirred up from near the reservoir sediments and mixed by the strong plumes induced by the diffusers. No clogging of the membrane diffusers was experienced, but the Unit 4 generator cooling system was clogged with sediment and organic growth due to the pumping action of the diffuser plumes. This necessitated outages for cleaning and chemical treatments to reduce organic buildup. This experience indicated a clear need for a means to spread the bubbles over large areas to reduce mixing and entrainment of the sediments.

Sixteen smaller PVC diffuser frames, measuring 100 foot by 120 feet, are shown in the accompanying figure and were successfully deployed in the Douglas Reservoir in1993. There were 80 hoses per frame for a total of 12 miles of porous hose. The system capacity was 3000 m³ per hour or 110 tons per day of oxygen. The redesigned oxygen distribution header was made of flexible hose. These diffusers have been used since 1993, to provide up to 2 mg/L of D.O. improvement in 16,000 ft.³ per second power discharges from the four turbines at Douglas Dam. Although these diffusers are effective and are still in use, the frames and buoyancy connections were too unwieldy and expensive for future designs.

In 1991 soaker hose equipment measuring 400' x 100' suspended on a PVC diffuser frame was built to support 50 foot long porous hoses. The common garden-variety soaker hose stretches slightly under pressurization so that O2 diffuses out through the walls. This was an attempt to distribute the oxygen bubbles more extensively to reduce mixing and oxygen demand from the sediment layer.

Early Hydropower Installations Using Membrane Diffusers

Douglas Dam, TVA: 1988

In 1988, a pilot oxygen diffuser system was installed on Unit 4 at TVA's Douglas Dam. Three bottom-anchored, steel diffuser frames with adjustable legs to fit bottom topography were lowered from a catamaran crane in front of the intake of Unit 4. Each 6-meter by 10-meter (20-foot by 33-foot) frame supported 78 membrane diffusers, as shown in Figure 2. Oxygen transfer efficiencies of about 72% were measured late in the DO season of 1988 when weak stratification conditions existed (Mobley, 1989). DO improvements in the releases were about 2 mg/L. However, during the peak of the 1989 DO season, the oxygen improvement in the releases dropped to nearly zero. This was attributed to oxygen demands stirred up from near the reservoir sediments and mixed by the strong plumes induced by the diffusers. No clogging of the membrane diffusers was experienced, but the Unit 4 generator cooling system was clogged with sediment and organic growth due to the pumping action of the diffuser plumes. This necessitated outages for cleaning and chemical treatments to reduce organic build-up. This experience indicated a clear need for a means to spread the bubbles over large areas to reduce mixing and entrainment of oxygen demands from the sediments.
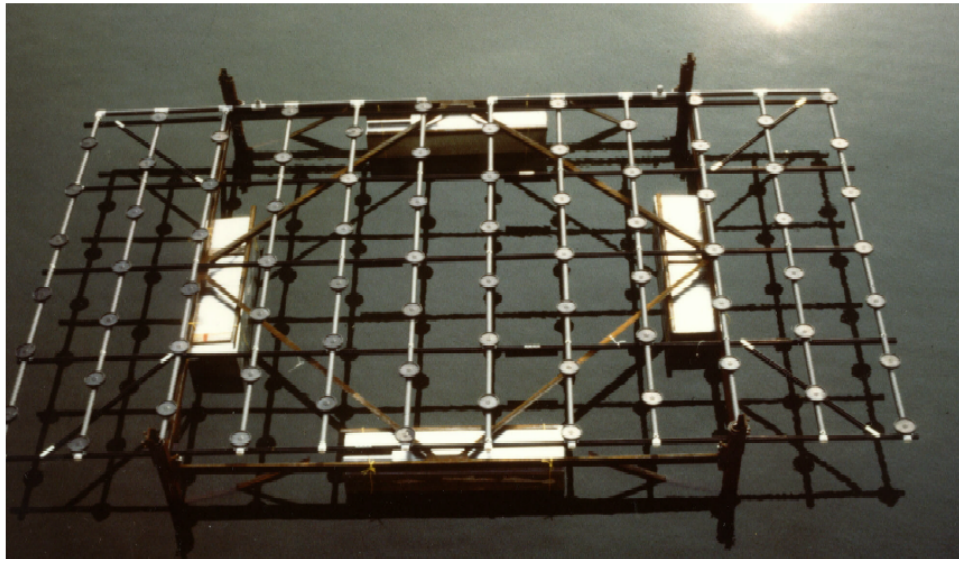
Installations using line diffusers

The following excerpts were taken from reports by Mark Mobley.

Normandy TVA 1994.

The next diffuser application at TVA was for a nonpower reservoir where aeration was desired to remove dissolved metals and hydrogen sulfide in the reservoir by aeration and precipitation. This system was supplied with compressed air. This installation was the first for the line diffuser design, and the clamps on saddle shoes for hose connections were

found to be expensive and leaky. The drilled holes to provide an orifice for flow control, were also found to be expensive and unnecessary.

Blue Ridge TVA 1994,

A linear arrangement of four, 1800 foot long diffuser lines were deployed in the fore bay to provide a 3 mg per liter dissolved oxygen improvement using 24 tons of oxygen system capacity per day. The design used small check valves at hose connections that were determined to be ineffective since the diffusers sank anyway, when left overnight. The long linear arrangement of the diffusers was found to provide insufficient oxygen to the small minimum flow turbine so an additional diffuser was installed immediately upstream of the intake tower.

Cherokee TVA 1994-1995.

Peak hydropower water flows at Cherokee dam can approach 20,000 ft.³ per second and despite having operational installations of both turbine venting and surface water pumps can require up to 2 mg per liter of additional dissolved oxygen improvement for the line diffuser system to meet 4 milligram per liter in the releases. The system capacity was 150 tons per day, with 48,000 lineal feet of line diffuser in the four bay. The system has automatic valves open to provide a high rate of oxygen flow while the turbines are in use. When the turbines flows are often small, oxygen bypasses the valves to maintain a background buildup of D.O. in the reservoir. The oxygen input from the diffusers provided oxygenated cold water in the fore bay that created a striped bass habitat during the warm summer sessions. High concentrations of fish lead to intense fishing pressure. But despite the repeated anchoring of boats in the area, no significant damage to the diffusers has been experienced. At this installation, the elastic cords for anchor attachment failed, allowing sections of the diffuser to float to the surface, creating a boating hazard. A new anchor connection using stainless steel cables was retrofitted by refloating each diffuser.

Fort Loudoun TVA 1995.

This mainstream, Tennessee River dam has hydropower flows approaching 38,000 ft.³ per second. But require only a small boost in D.O., mostly associated with reduced flows during weekends. The Fort Loudoun application included a single 10,000 foot long line diffuser used to spread oxygen input over the reservoir volume of an average day's generation. The diffuser was equipped with progressive orifice sizes at the hose connections to obtain uniform flow over the entire length. The installation was complicated by intense recreational boat use and

commercial navigation traffic. The elastic cord anchor connections were redesigned during this installation and retrofitted on the first diffuser.

Hiwassee Dam TVA 1995.

The original designs for the Hiwassee reservoir diffuser system were to use air but the total dissolved gas limitations in the tailrace shifted the design from air to oxygen. The installation of an on-site pressure swing absorption oxygen generation system was attempted for this application with unsatisfactory results. The diffusers are now supplied with liquid oxygen storage tank.

Watts Bar TVA 1996.

Watts Bar is another mainstream hydropower project with flows and oxygen requirements similar to Fort Loudoun. The diffusers were deployed to oxygenate an average daily flow volume and a more compact diffuser placement was utilized immediately upstream of the dam to provide for the increased oxygen needs during initial or single turbine operations. The multi-diffuser design used in the immediate fore bay, proved to be difficult to deploy and retrieve.

Buzzard Roost Hydroelectric Station, Duke Energy 1997.

The line diffuser at Buzzard's Roost was installed to provide enough oxygen input to allow Duke Energy to meet the FERC water quality requirements at the site. This installation included 9000 feet of line diffuser in the shallow excavated hydropower intake channel. The diffuser lines were placed within 20 m of each other in only 40 foot of water as compared with a typical spacing of 100 foot gaps.

Summary of existing line diffuser installations.

A total of 153,000 feet of line diffusers have been installed at the eight reservoirs described above and three other applications. The diffusers have required no maintenance of the inspection of the bubble pattern at the beginning of each season. Reservoir diffuser installations and other aeration applications have resulted in improved conditions in the hydropower tail waters, according to Scott *et al*. 1996. Installation costs of line diffusers have been $25-$30 per foot.

The Androscoggin River in Maine has a minimum flow of 1700 ft.³ per second and requires supplemental oxygenation from June the first until September the 30th, the deepest part of the forebay is 60 feet, and the oxygen transfer requirements are 40,000 pounds per day. The ambient D.O. is 5 mg/L and the design D.O. minimum is 6.5 mg/L. Additional mechanical aeration of Gulf Island Pond is a critical component of the overall plan to bring the Androscoggin River into D. O. attainment. The current model indicates that a total of 150,000 pounds per day to 210,000 pounds per day of oxygen must be supplied based on the current transfer efficiency of about 30%. This is in combination with additional controls at the paper mills in order to bring Gulf Island Pond into attainment for D.O.. In addition, the model indicates that attainment of D.O. criteria everywhere in Gulf Island Pond cannot be attained with a single point injection system at its current location. Multiple point oxygen injection systems are needed, unless there is sufficient proof to show that the attainment can be met using a different configuration.

The present oxygen supplementation system injects pure oxygen into fine bubble diffuser plates located at a depth of approximately 30 feet within the Androscoggin River. The diffuser loading rate is about 2 feet per minute. Coalescence of fine bubbles occurs and fouling of the diffusers has been noted over time.

Figure 9
WASP Model Segmentation for Gulf Island Pond

Due to the biological oxygen demand in wastewater discharges from the three paper mills located on the Androscoggin River and the sediment oxygen demand of the river due to the impoundment of the Androscoggin River created by the Gulf Island dam, the D.O. content that is required for class C waters may not be achieved during the summer months of July, August and September. Consequently the paper companies and Central Maine Power Company entered into an agreement to oxygenate the river.

The State of Maine, Department of Environmental Protection board requires that 27,000 pounds of oxygen per day be dissolved into the river water column. This requires a minimum 73,000 pounds per day of oxygen delivered to the river by the oxygen plant based on 35% O2 absorption efficiency. It is expected that this level of oxygen will meet water quality standards over most of Gulf Island Pond during July, August and September. A system was designed to introduce oxygen approximately 4 miles north of Gulf Island Pond through fine bubble porous ceramic diffusers which are located along the river bottom approximately 30 feet below the surface of the water.

Future oxygen supplementation requirements are from 40,000 to 70,000 pounds of oxygen per day to Gulf Island Pond. It is proposed to use 12 foot diameter by 18 feet
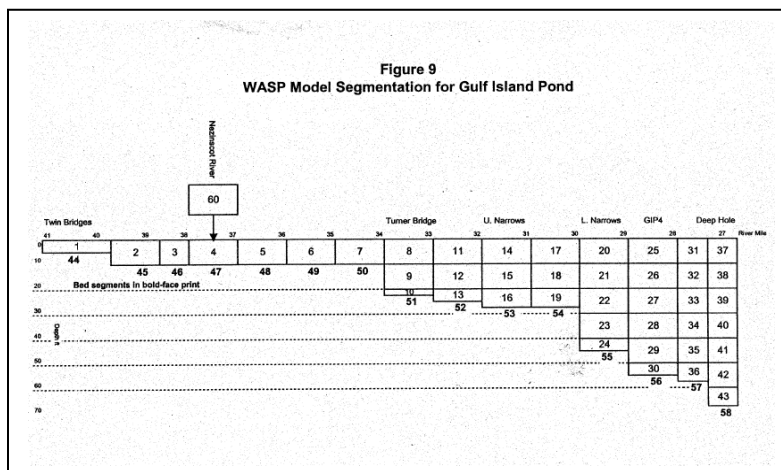
high Speece Cones, each capable of dissolving 10,000 pounds of oxygen per day. A 100 HP submersible pump will move water through the oxygenation cones. The water flow will be 30 ft.³ per second against 25 foot of head and contain 60 mg/L of D.O. in the discharge. Oxygen absorption efficiency of over 90% is specified and the unit energy consumption will be approximately 400 kWh per ton of D.O.. The discharge will be diluted quickly by a combination of diffuser and banana propeller pumps.

In order to transport the oxygenated discharge from the oxygenation cones at the dam to the upstream pond area, each will be equipped with a 7 foot diameter 10 HP banana propeller pump capable of moving about 200 ft.³ per second horizontally under negligible head.

Life Cycle costs are strongly affected by the O2 absorption efficiency achieved in the oxygenation system as shown in the following table.

Table. Comparison of % O2 Absorption and Costs for 40,000 lb D.O./day

%O2 Absorp	O2 Added	O2 Lost	Cost of O2 Lost	Present Worth O2 Lost
	ton/yr	ton/yr	$/yr	$
100	2000	0	0	0
90	2200	200	66,000	693,000
75	2670	666	222,000	2,310,000
60	3330	1330	444,000	4,620,000
50	4000	2000	666,000	6,930,000
40	5000	3000	999,000	10,400,000
25	8000	6000	2,000,000	20,800,000

Amsterdam, Netherlands, Canal Mobile Barge Oxygenation

There is at present no complete sewer system operating in the lovely concentric canals of central Amsterdam, which therefore continually receive raw sewage directly. The low flow velocity in addition to deep waters, and the pooled nature of the canals, all contribute to low reaeration rate and zero D.O. levels. Hydrogen sulfide generation thus mars the historic picturesqueness of the area and assaults the urban population.

A motorized barge, containing a liquid oxygen storage tank and an oxygen injection system was deployed to withdraw canal water, super oxygenate it under elevated pressure,
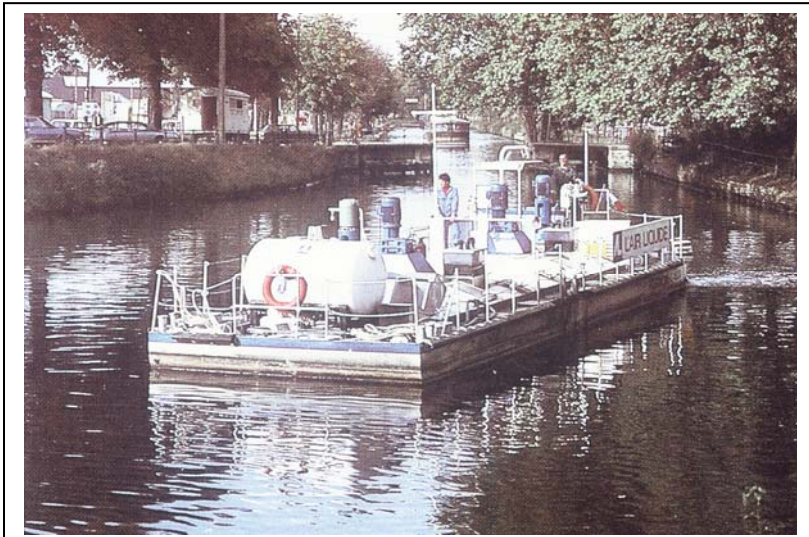
and then discharge it back into the canal. The barge system has been successful in increasing D.O. concentrations in the canals sufficiently to prevent hydrogen sulfide production.

Shanghai Harbor, Suzhou Creek, China, Mobile Oxygenation

As Shanghai has grown commercially to become China's largest industrial center, Suzhou Creek has suffered increasingly severe pollution. From the 1920s the river began to smell and turn a blackish color, causing the extinction of fish and shrimp in the river. Until 1978, the entire Shanghai section of the Suzhou Creek was thoroughly polluted.

Stretches of the 125 km Suzhou Creek have experienced anaerobic conditions, which means there are insufficient levels of oxygen to support fish or other aquatic life. Pumping oxygen into the water, by means of the barge, will assist the natural process of decomposition of pollutants and the restoration of oxygen levels needed to prevent H2S odors and sustain aquatic life.

A decade later, the Shanghai municipal government started a cleanup project to restore the river. A total of 8.7 billion yuan i.e. one billion US dollars, was spent completing the first stage of work on the project. The plan to clean up Suzhou Creek was launched in 1998, with the creation of the Shanghai Suzhou Creek Rehabilitation and Construction Company (SSCRCC). Its goal was to rehabilitate Suzhou Creek,

to enable it to reestablish an ecosystem and raise public health standards for nearby residents.

British Oxygen Corp. designed and supplied the environmental technology for China's first mobile oxygenation barge. The self-sufficient barge represents the first step in a 12 year plan to rehabilitate Suzhou Creek. The Suzhou Creek project is China's most ambitious water reclamation project to date. The mobile oxygenation system is capable of generating 5 tons of oxygen per day and injecting it into venturi jets which discharge into the water at 20°C with a concentration of 6 mg/L D.O.

The oxygenation barge, which was officially handed over to the Chinese government in November 2001, contains a BOC Novox TM oxygen generator and two Vitox TM venturi oxygen injectors. Water from Suzhou Creek is withdrawn from the river, oxygenated on the barge at a rate of 5 tons per day, and then returned to the river via 20 Vitox venturi distribution nozzles mounted on each side of the barge.

This is the latest version of Thames Bubbler and Thames Vitality technology that BOC had developed for use in two barges used on stretches of the Thames River in England. Two delegations from SSCRCC, visited Vitality and talked with BOC engineers in Guilford, UK before BOC was awarded the contract for the Suzhou Creek project.

At the official dedication ceremony, which took place in Shanghai on November 2, 2001, Chinese environmental officials said they had originally planned to build several land-based oxygenation stations along the banks of Suzhou Creek, but decided it would be more effective to use a mobile oxygenation station to deal with shock pollutant loads during emergencies. An SSCRCC representative said, " the barge can go wherever it is needed to improve the oxygen level quicker and cultivate beneficial aerobic bacteria."

The $1,600,000 barge will be working on a one-month trial basis. More barges are expected to be built to improve Harbor water quality even more.

II. Proposed Appropriate Sites for Oxygen Supplementation to Water Bodies

Oxygenation technology is being considered to remediate D.O. depleted waters in the following locations:
Cardiff Bay, England
Stockton, California Deep Water Ship Channel.
Onondaga Lake, New York
Chicago Canal System, Illinois
Brownlee Reservoir, Snake River, Idaho
Hood Canal, Washington
Manchester, England Ship Channel.
Jamaica Bay, New York.
San Diego water reuse reservoir.
New York City water supply reservoirs.
Venice Lagoon, Italy.
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Cardiff Bay, England, Speece Cones on Oxy/Cat Mobile Barges

The barrage erected across Cardiff Bay in about 1995 to isolate tidal activity outside and maintain a constant pooled water surface inside the barrage has impounded approximately 440 acres of water in a permanent pool behind the dam. The pool prevents the tidal mud flats from being exposed and their associated bad odors are avoided. It has resulted in a real estate boom on the water front. However characteristically the pooled water is deficient in D.O.

An air diffusion system designed by Ken O'Hara was adopted, but it could not satisfy D.O. standards in the harbor under all conditions. Therefore a mobile oxygenation unit was proposed to serve the impoundment that could be moved to remediate specific oxygen depleted areas. A system was proposed, which incorporated Speece Cone oxygen

transfer technology in combination with a twin hauled barge. The design features an adjustable discharge boom, which can deliver a super oxygenated sidestream horizontally through this diffuser to variable depths of between 1 to 8 m in the water column.

More than 90% oxygen absorption can be achieved, while consuming 1100 kWh per ton of D.O. added from an on barge oxygen storage tank. The Oxy/Cat dimensions are 15 m length and 7 1/2 meters width with a loaded draft of 0.75 m and light air draft of 3.5 m. The system is comprised of two Speece Cones, a LOX tank capable of holding 6 tons of liquid oxygen and two Perkins, 185 D diesel engines which drive two 12 inch pumps to move the water through the oxygenators.

A comparison of the Liverpool Water Witch Marine and Engineering Co. Ltd.'s/ECO2 Oxy/Cat system with the BOC Vitox oxygenation barge reveals several important differences:

Speece Cone oxygenation system.
- 90 % oxygen absorption regardless of the depths to which the water is discharged.
- Gas transfer accomplished **before** discharge into the bay.
- Closed system readily monitored using a flowmeter to determine flow rate in inlet an meter to measure D.O. prior to discharge.
- No effervescent loss of D.O. due to instant dilution.
- Absorption efficiency not dependent upon water column D.O. concentration.

Vitox System.

- Percent absorption dependent upon deeper depths.
- Gas transfer occurs after discharge into the baying causing turbulence.
- An open system, not easily monitored for flow rate and D.O. levels.
- Dissolving takes place during rise of bubbles to the surface in the water column.
- Absorption efficiency depended upon D.O. concentration in water column.
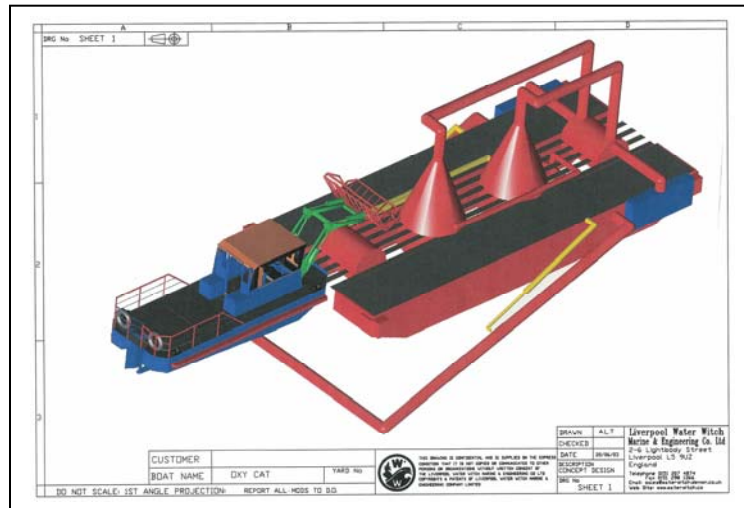
Stockton Deep Water Ship Channel

Evaluation of Aeration Technology for the Stockton Deep Water Ship Channel.
Report to CAL FED Bay Delta Program.
Sacramento, California.
Dr. Russ Brown.
April 19, 2002.

Quoted from the Executive Summary

This report describes the scientific background for quantitatively understanding aeration processes that transfer oxygen between the atmosphere (gas) and a water volume (dissolved gas). Although water (H_2O) is composed of 89% oxygen, fish and aquatic organisms require D.O. gas (O_2) for respiration and cannot utilize the oxygen in the water molecules. The natural reaeration that occurs at the surface of the San Joaquin River and the Stockton Deep Water Ship Channel (DWSC) is described to introduce the equations and coefficients that are used to quantify this process.

The basic methods that have been used to augment or artificially increase this oxygen gas transfer process in rivers and lakes (or reservoirs) are then described. The performance of the existing Corps of Engineers jet-diffuser device is summarized, and the engineering feasibility of alternative methods to increase D.O. (DO) concentrations in the DWSC with aeration technology are compared. Each alternative is described for possible application to the DWSC worst-case summer design condition where the DO recorded at the Rough & Ready DO monitoring station is assumed to be 2 mg/l below the DO objective for the DWSC.

Figure 1 shows the location of the City of Stockton River water quality stations within the DWSC. The Department of Water Resources (DWR) continuous DO monitoring station is located at the downstream end of Rough & Ready Island, near the R5 sampling station. Data from these stations are used to estimate the DO deficit below applicable water quality objectives for the DWSC (i.e., 5 mg/l from December through August and 6 mg/l from September through November). This DO deficit is the necessary amount of DO augmentation that would be necessary to meet the DO objectives in the DWSC. Based on the daily minimum DO concentrations at the Rough & Ready monitoring station, a total of about 1,000,000 pounds of oxygen would have been needed in the summer of 2001. An aeration device that delivered about 10,000 lb/day would have satisfied the measured DO deficit during the summer of 2001. The required amount of DO supplied by aeration in 1999 and 2000 would have been somewhat less, although the 10,000 lb/day capacity would likely have been needed in each year. For an assumed DWSC reaeration transfer distance of 0.5 m/day with a DO deficit of 4 mg/l, reaeration will supply about 18 pounds of oxygen per acre per day. There are about 250 acres between R3 and R5, so the reaeration in this portion of the DWSC would be about 4,500 lbs/day. The DO concentration increase from one day of reaeration would be about 0.25 mg/l (i.e., 0.06 * 4 mg/l). This is only a moderate reaeration term compared with the RWCF and SJR river loads of BOD, and the assumed transfer velocity of 0.5 m/day is uncertain.

D.O. Concentration Pattern in the DWSC

The DO concentration patterns in the DWSC are controlled by reaeration and algae production of DO as well as BOD (and SOD) decay processes. The BOD loads originate from the Stockton RWCF effluent and from upstream SJR sources, as well as from sediment oxygen demand and algae biomass growing within the DWSC. The City of Stockton water quality model uses a typical first-order DO sag equation coupled to the governing hydrodynamic equations for tidal flow within the DWSC. The current model does not include effects from stratification on algae growth and reaeration (i.e., mixed depth dynamics). The DO modeling simulates the longitudinal DO pattern and identifies the location of the lowest DO concentration (greatest DO deficit.

Figure 2 shows the measured minimum and maximum DO concentrations at the DWR Rough & Ready monitoring station during 2001. The minimum DO concentrations were generally about 3 mg/l during the worst-case episodes. The saturated DO concentration is shown for comparison to indicate that the minimum DO concentrations were generally 4-5 mg/l less than saturation during the summer period. The minimum DO concentrations were therefore about 2 mg/l less than the DO objective of 5 mg/l during these worst-case episodes. The maximum DO concentrations measured during the afternoon are influenced by algae photosynthesis and are usually about 2-3 mg/l higher than the minimum DO values, and may approach saturation concentrations on some days. The reaeration rate, which is controlled by the DO deficit, is therefore less during these afternoon periods. A DO sag may also occur after September 1 when the DO objective changes to 6 mg/l. The pattern and magnitude of DO sag in September is similar to conditions prior to September because water temperatures are slightly cooler and the saturated and measured DO concentrations are slightly higher.

Figure 3 shows the minimum DO pattern measured in 1999 along with the UVM net flow estimates during the year. The daily calculated DO required to satisfy the DO target concentration (DO objective + 0.5 mg/l) are also shown. The DO concentration was below the DO target concentration from about July through September of 1999 (although the DO in October was not recorded). The daily DO deficit was often 10,000 lb/day with a few peaks of 15,000 lb/day. An aeration device with a daily DO delivery of 10,000 lb/day would likely have maintained the DO concentration in the DWSC at the DO target during 1999. The total DO deficit in 1999 was at least 650,000 pounds, although a deficit might have also occurred in October. The total cost for oxygen (at $0.10/lb) in 1999 (including some in October) would have been about $75,000.

Figure 4 shows the minimum DO pattern measured in 2000 along with the UVM net flow estimates during the year. The DO concentration was below the DO target concentration from about mid-June through September of 2000 (although the DO in October was again not recorded). The daily DO deficit was often 10,000 lb/day with a few peaks of 15,000 lb/day. An aeration device with a daily DO delivery of 10,000 lb/day would have maintained the DO concentration in the DWSC at the DO target during 2000. The total DO deficit in 2000 was at least 475,000 pounds, although a deficit might have also occurred in October. The total cost for oxygen in 2000 would have been about $50,000.

Figure 5 shows the daily calculated DO source required to satisfy the DO target concentration in 2001. The DO concentration was below the DO target concentration from early June through early October of 2001. The daily DO deficit was often 10,000 lb/day with a few peaks of 15,000 lb/day. An aeration device with a daily DO delivery of 10,000 lb/day would have maintained the DO concentration in the DWSC at the DO target during 2001. The total DO deficit in 2001 was about 1,000,000

pounds. The total cost for this oxygen would have been about $100,000 in 2001.

Aeration Design Conditions

These worst-case summer conditions have been previously characterized with the results from DWR Rough & Ready Island DO monitor as well as City of Stockton water quality monitoring results (Jones & Stokes 1997, 2001).   Net SJR flows through the DWSC during low flow summer period of about 500 cfs can be expected to occur on a routine basis, and the travel time for water between R3 and R6 at 500 cfs is about 10 days (because the DWSC volume from the turning basin to R6 is about 10,000 acre-feet). Monitoring data indicates that similar DO sag concentrations can occur to a flow of about 2,000 cfs. Generally, the maximum DO sag is located further downstream in the DWSC as flows increase. When flows exceed 2,000 cfs, the magnitude of the DO sag within the DWSC is reduced due to shorter residence times, higher natural reaeration rates, or lower BOD concentrations entering the DWSC. As hydraulic residence time decreases with increasing flow, the time available for BOD decay is reduced. At higher streamflow rates, a greater portion of the BOD load passes through the DWSC out to the other Delta channels. Higher flows may reduce the SJR concentrations of BOD and dilute the RWCF effluent BOD loads.

At a flow of 1,000 cfs, a 2 mg/l DO decline below the 5 mg/l objective is equivalent to a daily DO mass deficit of 10,800 lb/day (i.e., $5.4 * 1,000 * 2 = 10,800$). This is the quantity of oxygen that needs to be added into the DWSC on a daily basis to result in average DO concentrations near the DO sag location that meet the Basin Plan DO objective of 5 mg/l. This is taken as the worst-case design capacity for the alternative DWSC aeration devices.

Figure 6 illustrates the major factors and processes that influence the DO concentration pattern within the DWSC.   The initial BOD concentration (and BOD decay rate) along with the sediment oxygen demand (SOD) govern the DO losses along the DWSC. The reaeration is the major source of DO and depends on the DO deficit (below saturation). The net flow controls the travel time as the water moves through the DWSC from R3 to R6.   An estimate of worst-case total BOD concentration is about 10 mg/l (equivalent to a 5-day BOD measurement of about 4 mg/l). At a flow of 1,000 cfs, this is a total BOD load of 54,000 lb/day. The City of Stockton RWCF and the SJR are the sources for this BOD load.   SOD has been estimated to range from 0.5 to 1.0 g/m^2/day and is assumed to be uniform throughout the DWSC (Litton 2001). This range of SOD exerts a daily oxygen demand of about 1,115 lb/day to 2,230 lb/day based on the channel bottom area (i.e., 250 acres) between stations R3 and R6. The origin of this SOD, however, may be settling of some of the total BOD from the river and RWCF discharge.

1) Reaeration depends on the estimated transfer velocity (i.e., 0.5 m/day) and the DO deficit. For an average deficit of 4 mg/l, the reaeration between R3 and R6 would add only about 4,500 lbs/day. However, the intermittent development of stratification near the water surface may restrict the reaeration of the DWSC. Algae photosynthesis in the surface of the DWSC will add DO but also increase the BOD concentration. Although the net effect of algae growth and respiration in a closed tank would be no change in DO concentration, the effects of algae growth in the DWSC are not well documented. It is apparent from this simple comparison that the BOD loading far exceeds the oxygen source from natural reaeration (with algae growth and respiration assumed to provide no net increase in DO). Artificial aeration or oxygenation will be needed to provide a balance in the DO budget within the DWSC.

2) One problem with the bubble devices as that the aerated water ends up on the surface where the DO may already be high, rather than in the bottom layer where the DO is lowest.
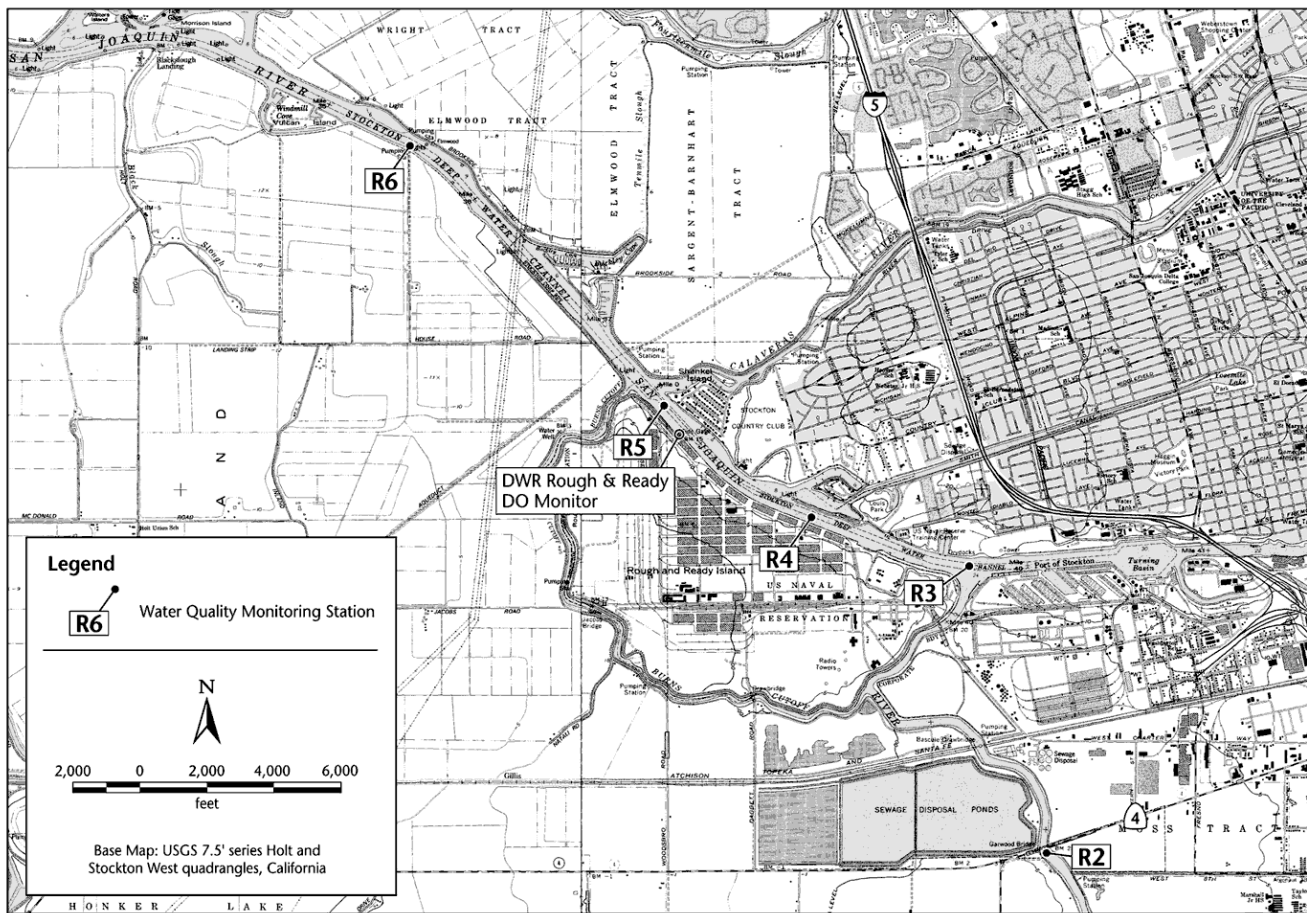
Figure 1
Stockton Deep Water Ship Channel Water Quality Stations

Jones & Stokes

Figure 2. DO Minimum and Maximum Measured at Rough & Ready DO Monitor During 2001

Minimum and Maximum DO at Rough & Ready Monitor

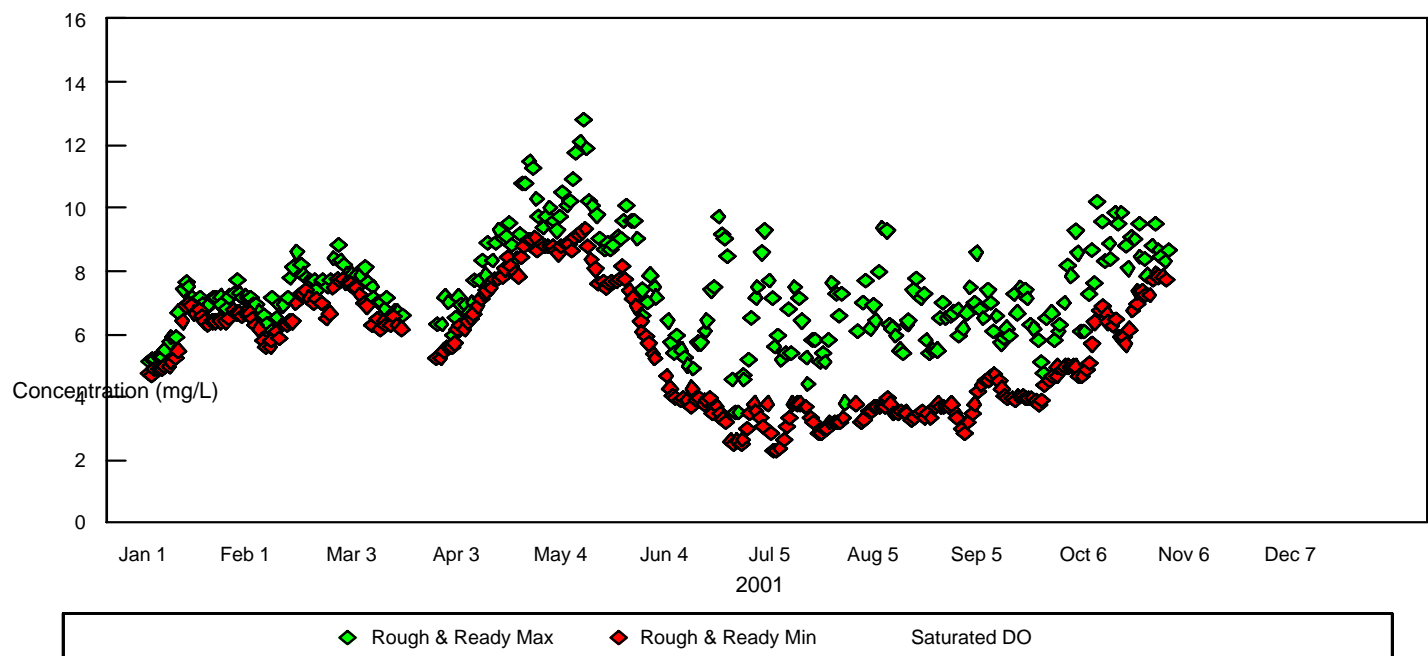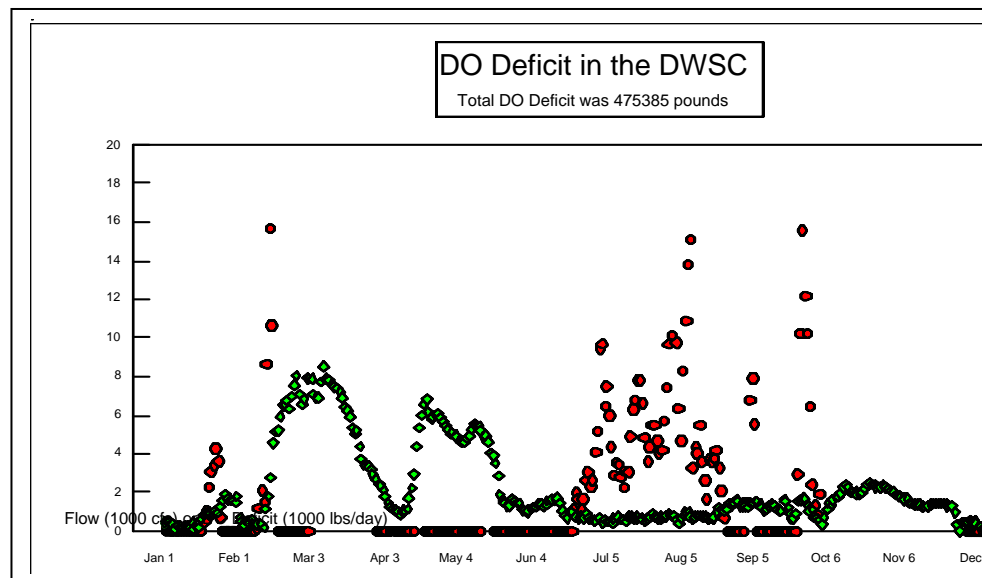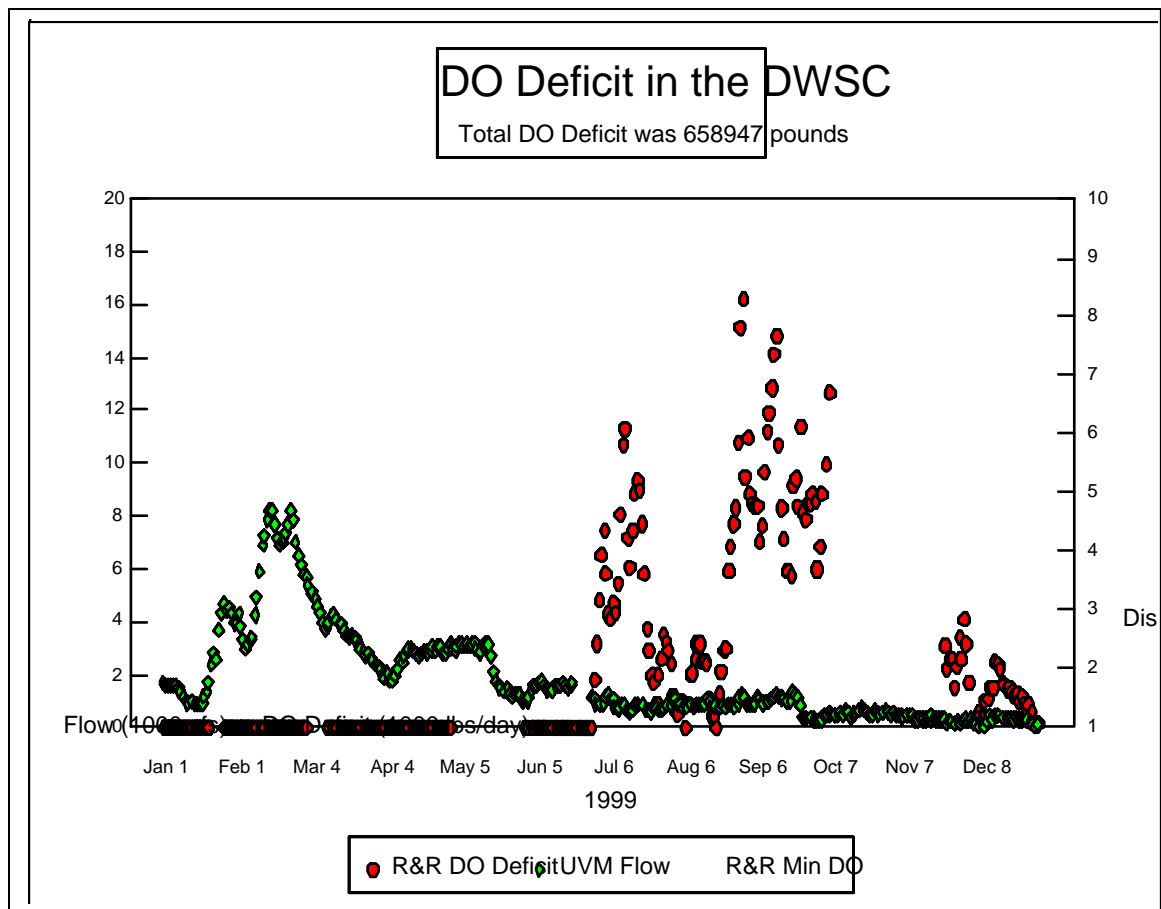◆ Rough & Ready Max   ◆ Rough & Ready Min   Saturated DO

33

Figure 3. Calculated DWSC D.O. Deficit During 1999.

Onandaga Lake Hypolimnion Oxygenation, Syracuse NY

Taken from US Army Contract Description

Onondaga Lake an urban lake located in metropolitan Syracuse, NY is approximately 4.6 miles long by 1 mile wide has mean and maximum depths of 35 and 63 feet respectively and a drainage basin of 248 square miles. The major hydrologic inputs to Onondaga Lake are several creeks and the Syracuse Wastewater treatment plant. The lake outlet is located at the northern end of the lake where it empties into the Seneca River. Onondaga Lake's present water and sediment quality and biological conditions are the result of more than a century of waste inputs. Contributing factors include extensive quantities of treated domestic wastewater, combined sewage overflows, various industrial wastes, runoff from urban and agricultural land and leaching of various substances from hazardous waste sites around the lake. Another likely factor is the probable release of mercury, phosphorous and other contaminants from the lake's bottom sediments. Fishing was banned in 1970 because of mercury contamination and currently, a fish advisory exists which severely limits fish consumption. Some of the water quality problems in Onondaga Lake result from the fact that the effluent from the municipal wastewater treatment plant represents approximately 20% of the annual inflow to the lake and 60 to 70% of the total inflow during low flow conditions. Pollutant loading in this effluent may contribute to low hypolimnetic D.O. concentration. In addition, during late summer and early fall turnover, Onondaga Lake has undergone temporary lake-wide D.O. depletion resulting in violation of NY State's minimum D.O. concentration of 4 mg/L for several weeks.

The hydraulic residence time in Onondaga Lake is about 3 months. During stratification the hypolimnion waters are basically stagnant while the inflow water flows over the top of the lake and out.

Preliminary recommendations are to supplement approximately 30 tons of D.O. per day to the lake hypolimnion for the next decade to satisfy the accumulated oxygen demand in the sediments and reduce the rate of mercury methylation.

Chicago Urban Canals Supplemental Oxygenation

   The urban canals of Chicago receive storm runoff and combined sewer overflows. Their impounded flow prevents periodic scouring of benthic deposits and also results in very limited reaeration capacity. Consequently prior to about 1990 the D. O. was often near zero for extended periods. Chicago's urban canal system is used for barge transportation as well as conveyance of treated waste waters away from the metropolitan area. Lake Michigan is a high-quality water resource that serves as the water supply for Chicago. By federal decree, only an annual average of 90 m³ per second of water could be diverted from Lake Michigan. A proposed system of 10 strategically placed diffused aeration stations having a combined reaeration capacity of 134,000 kg of oxygen per day was proposed to maintain minimum D. O. concentrations. However, 18 m³ per second of Lake Michigan water would have still been required as an integral part of this supplemental reaeration scheme.

   An economically competitive supplemental reoxygenation system utilizing pure oxygen and a system of five reoxygenation stations was proposed which would maintain the D. O. standards and require no diversion of Lake Michigan water. The diverted water thus saved was freed to serve as a much-needed water supply for communities in the metropolitan area. The reoxygenation stations proposed were two U-Tubes of 75 m depth and capable of raising a sidestream from the canal up to 35 mg/L D. O. This sidestream would then be blended with the canal flow to raise the canal D. O. to approximately 15 to 25 mg/L. Negligible stripping of this supersaturated canal D. O. would have occurred because of the low reaeration rate of this pooled canal. Yet the number of required reaeration stations was markedly reduced from 10 to 5 over the case where air would be used as the oxygen source. Only two reoxygenation stations were required on the canal using U-Tube oxygenation and pure oxygen injection versus 10 for diffused aeration station. Three U-Tube pure oxygen stations were to be located on the outfall of the three major wastewater treatment plants.

   The Chicago Canal system consists of three segments, North Shore 12.8 km long, Main 48 km long main and Calumet Sag 26 km. These canals connect with the original river channels to form a 130 km system. The average depth varies from 3.6 m in the North Shore Canal to 7.6 m in the main with width varying from 21 m in the North Shore Canal to 60 to 90 m at places in the Main and Calumet sag segments.

   Dry weather flows result in extended travel times of four days in the North Shore, five days in the main and four days in the Calumet sag canals. Combined sewer overflows discharge into the canal system to prevent local flooding. The average frequency of combined sewer overflows was once per four days before the large tunnels were constructed for storage of storm overflows. The average BOD of the overflow events is 273,000 kg. The long-term effects of these combined sewer overflows is the accumulation of sludge deposits of 1 to 2 m depth in the canal system, causing the benthic deposits to exert an oxygen demand of 64,000 kg per day.

   The stations would pose no interferences to navigational use of the waterways. Each would be designed to oxygenate a sidestream effluent of canal water drawn out of the main flow through a screen into a pump. The flow to be oxygenated would be pumped into the U-Tube against approximately 4 m of head by a low lift pump station. Pure oxygen would be injected in the down flow leg of the U-Tube at a rate required to

produce the desired discharge D. O.. The upflow leg of the U-Tube would discharge into a diffuser pipe located on the bottom of the canal at right angles to the direction of flow and approximately 20 meters downstream from the intake screen.

Main canal. The low flow at the head of the main canal is approximately 19 m³ per second. By raising the dissolved oxygen concentration from 4 to 14 mg/L. The D. O. standards would be satisfied with no discretionary diversion from Lake Michigan until the flow reached the West Southwest sewage treatment plant. The U-Tube would add 34 mg/L of D. O. to a flow of 7 m³ per second.

Brownlee Reservoir on the Snake River, Idaho

Taken from "Application for Certification Pursuant to Section 401 of the Federal Clean Water Act for the Relicensing of the Hells Canyon Hydroelectric Complex. FERC No. 1971 Submitted to Oregon Administrative Rules Chapter 340, Division 48 , July 2003

Brownlee Reservoir is on the Snake River between Idaho and Oregon and is part of the Hell's Canyon Complex of hydropower dams. The water quality standard is 6.5 mg/L. Currently D.O. levels in Brownlee Reservoir do not always meet the D.O. targets nor are they adequate to support all designated beneficial uses. D.O. in Brownlee Reservoir can become severely degraded, especially during summer, a condition that has occasionally caused fish mortality.

The D.O. was below this target 55% of the time in Brownlee Reservoir and the metalimnion had the highest number of measurements below target. Excessive algal profileration is reported to be the cause of the D.O. deficiency and a phosphorous reduction has been recommended.

To fulfill regulatory requirements it is proposed to supplement 1450 tons of O2 per year into Brownlee Reservoir into the transition zone or the upstream end of the lacustrine zone.

Percy Priest Lake

The basic purpose of the Percy Priest Lake oxygenation system is to meet the water quality discharge criteria in the hydropower discharges. This involves D.O., Fe, Mn, and H2S. Is it possible to leverage the engineering solution such that significant additional benefits can be realized without additional costs? It seems kind of a shame to just meet the letter of the law when significant environmental enhancement of the hypolimnion could be realized for not additional cost. In this proposed oxygenation design there are even considerable savings in capital costs as the hypolimnion is enhanced and the discharge water quality criteria are still achieved.

The real burden of the oxygenation system for Percy Priest lies in accommodating the peaking power releases - which may occur only once or twice a summer. An oxygen demand of 37 tons/day is required in the dam vicinity where it will have least enhancement to the fishery habitat. So much oxygen is put into the reservoir for so little

time - perhaps a few hours! Two thirds of the total oxygen transfer capacity is required just to meet these sporadic releases.

Why does so much oxygen have to be added at the dam vicinity? Because it is *not* in the water already. If it was already in the water, there would be no need for such large instantaneous oxygen dissolution capacity.

If it is assumed that a given amount of oxygen is required per season, why not buy it a few months early and store it in the hypolimnion? This would require that oxygen injection would have to be initiated about one month earlier than normal when the hypolimnion D. 0. dropped to 5 mg/L to maintain it at that level. In such a case there would be no need to instantaneously meet a sporadic discharge event. Maintenance of 5 mg/L of D.O. in the water column does not cause a significant increase of oxygen demand from the sediments or the water column.

To avoid high peaking oxygen demands, it is necessary to determine the maximum discharge-duration event. If it is assumed the maximum discharge would be 4600 cfs for 7 days, this would be 9000 acre-ft per day of which 80% comes from the hypolimnion or 7200 acre-ft per day times 7 days = 50,000 acre-ft. Since the hypolimnion has a volume of 178,000 acre-ft (below elevation 470 ft.) there is sufficient hypolimnion volume to meet this design event. A volume of 50,000 acre-ft contains 340 tons of oxygen at 5 mg/L.

If it is assumed that the projected oxygen use per season is 2500 tons and the season is 170 days, the base rate of oxygen supplementation is 15 tons per day.

If it is not sufficient to just dissolve the oxygen, it needs to be moved throughout the hypolimnion. The major cost of this oxygen supplementation project is getting the oxygen in solution. A relatively minor cost is involved in moving it horizontally throughout the hypolimnion. To accomplish this function, it is proposed to utilize 3 - 10 HP 8 ft diameter, horizontal axial flow pumps capable of mixing 200 cfs each. The mixing characteristics of such a pump are that it will reach 3 km away in I day and 6 km away in 6 days.

PROPOSED OXYGENATION LAYOUT

A Speece Cone is proposed to be located at the Corps boat dock and has the flexibility of delivering the highly oxygenated side stream in the direction of the dam, in the direction parallel to the dam across the reservoir or upstream in the reservoir in the direction opposite to the dam. Its "zone of influence" can be enhanced over 6 km away within a week by the use of the aforesaid pumps.

It is recommended for this design that a Speece Cone be placed in the old river bed channel near the Corps boat dock. A 10 ton/day Pulsed Swing Adsorption (PSA) oxygen generator would supply this Cone.

An addition Speece Cone is recommended at approximately 5 miles upstream (below Hobson Pike) and having a capacity of 5 tons/day of oxygen dissolution capacity. It would be fed by a PSA oxygen generator of 5 tons/day capacity.

There would be 3 locations where a 200 cfs 10 HP large diameter, horizontal axial flow pump would be located. One would be located at each Speece Cone location and a third would be located above Elm Hill Marina. This third large axial flow pump would move oxygenated water pumped from the Cone at the Corps boat dock and move it further upstream.

ELEVATION VIEW OF TYPICAL SPEECE CONE
WITH HORIZONTAL FLOW PUMP
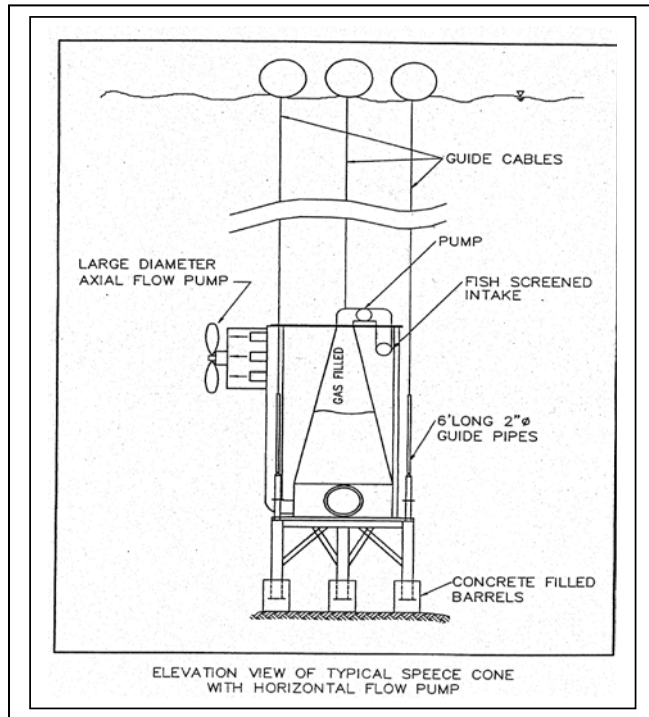
Gowanus Canal New York City

Following is a proposal for supplemental oxygenation of the Gowanus Canal. It is understood that 6100 lbs of D.O. is to be supplemented each day and that a D.O. of 8 mg/L is to be maintained in the canal under summer temperatures of 25 ^{o}C. The canal is assumed to be 20 ft. deep. D.O. C_{sat} for air at mid-depth would therefore be 10.4 mg/L (1.3 atm at mid-depth x 8 mg/L C_{sat} at 25 ^{o}C.) The D.O. deficit at which an aeration process would be working would therefore be 10.4 – 8.0 = 2.4 mg/L.

Super oxygenation technology for discharge horizontally through a diffuser located off the bottom of the canal (to prevent sediment suspension) where it is rapidly diluted down to 8 mg/L D.O. is recommended. This also accomplishes mixing and transport of the D.O. along the canal. A system would raise the D.O. in a sidestream to about 90 mg/L and guarantee over 90% dissolution and retention in the water. The size of this Speece Cone system would be nominally 8 ft in diameter and about 20 ft tall supplied with a 200 HP pump.

The system has an energy consumption of about 1000 kwhr/ton of D.O. added. This would be about $300/day for electricity at $0.10/kwhr to add 6100 lbs D.O. per day. The entire system can be mounted on a barge moored on the side of the canal or placed on land where space is available.

For a permanent solution, the oxygenation vessel could be placed in an excavated caisson about 40 ft deep so that it could use the hydrostatic pressure instead of pumped pressure to achieve superoxygenation. This would reduce the energy consumption to less than 300 kwhr/ton of D.O. as has been done for an industrial client in Oklahoma. In this case 30 cfs was pumped through an oxygenator and raised the discharge D.O. to 60 mg/L in water that was 25 ^{o}C. It then entered a 5-mile long pipeline flowing full to prevent any hydrogen sulfide formation during transit. This system dissolves about 10,000 lbs of D.O. per day. A 40 HP pump is used to move water through each oxygenator.

New York Water Supply Reservoirs

The New York City Water Department withdraws cold hypolimnion water from stratified New York State reservoirs except during summer months when complete D.O. depletion occurs in some of the reservoirs caused by algae proliferation in warm surface waters. Under such anaerobic conditions, Fe, Mn and H2S production is exacerbated by algae decay, consuming all the D.O. Since no subsequent treatment has been provided to date, these reservoirs must be taken off line until colder weather results in destratification.

Direct supplementation of oxygen to the hypolimnion, however, would avoid this problem while not destratifying the reservoir. In addition the potential problem of dissolved nitrogen supersaturation which often arises when using air may be avoided when superoxygenation is utilized as the treatment protocol.

For stratified reservoirs with D.O. deficiency in the hypolimnion, oxygen can be dissolved directly into the hypolimnion to effectively offset the oxygen demand from algae settling down from the euphotic zone as well as sediment oxygen demand. This would be

similar in concept to the Camanche Reservoir hypolimnion oxygenation system utilizing the Speece Cone.

San Diego Water Reuse Reservoirs

One novel application of hypolimnion oxygenation with induced horizontal flow propagation is in regions which have a chronic summer water shortage. Reuse of treated wastewater to augment the water supply is being considered in San Diego. It is desirable to have a storage period delay of over a month after the wastewater is treated before it is used as a water supply. The treated warm wastewater would be discharged and stored in the epilimnion providing the requisite storage delay before reuse and the hypolimnion would have to be supplemented with oxygen to prevent water quality deterioration throughout the stratification season.

Manchester Ship Channel Eng**land**

Presently supplementation of D.O. is practiced in this ship channel with aeration techniques that incorporate air aspiration into Venturi ejectors. Due to the inability to meet the target D.O. criteria, superoxygenation has been recommended.

Hood Canal Washington

Hood Canal is a long narrow branch off Puget Sound. It is about 50 km long, 2 km wide and an average of 100 m deep with an entrance sill of 50 m. Maximum depth is about 200 m.   Persistent stratification is maintained from gradients in both salinity and temperature. There is a strong density difference located at 5 to 10 m depth. Strong water column stratification with low dissolved oxygen levels are typical throughout the year but are more pronoumced in the southern portion of Hood Canal and during the Fall.   Because of the canal's depth and shape, the water exchange is slow, taking about a year for the canal to exchange its waters with Puget Sound. Fish and invertebrate mortalities are believed to be due to low dissolved oxygen . ("First Record of a Heterosigma Akashiwo Bloom in Hood Canal Washington, USA. By Connell, L.B., Newton, J.A. and Craig, S. D.
Weather conditions can cause upwelling in the ocean so that the water flowing into the Puget Sound is also lower in oxygen and higher in nutrients. The daily D.O. demand in the lower regions of the canal is in the order of 100 tons per day.

Venice Lagoon Italy

Storm tides which sometimes flood the beautiful city of Venice, Italy are gradually undermining its magnificent architecture. Future efforts to prevent flood damage, however, must accommodate an additional set of problems. Since the city still has no sewerage collection and treatment system, should tidal gates be built to isolate the lagoon during high

tide emergencies to prevent further architectural and artistic deterioration, severe oxygen depletion could soon occur in the lagoon. In the absence of flushing tides the undesirable visual spectacle of algae scum forming and the possibility of serious fish kills occurring would have to be addressed in the design criteria for tidal gate use. This lagoon is an excellent candidate for superoxygenation to achieve water quality objectives.

Jamaica Bay, New York

Literature Cited:

Ashley, K. I. 1985. Hypolimnetic Aeration: Practical Design and Application. *Water Research 19:735-740.*

Ashley, K.I., S. Hay, and G. H. Scholten. 1987. Hypolimnetic Aeration: Field Test of the Empirical Sizing Formula. *Water Research 21:223-227.*

Ashley, K. I. 1990. Preliminary Design for a Hypolimnetic Aeration System for Newman Lake. Washington State University Contract No. 10004. Report to Spokane County.

Bernhardt, H. 1967. Aeration of Wahnback Reservoir Without Changing the Temperature Profile. *J. Amer. Water Works Assoc. 59:943-963.*

Bernhardt, H. 1974. Ten Years Experience of Reservoir Aeration. *Progr. Water Technol. 7:483-495.*

Beutel, M.W. and A.J. Horne. 1999. A Review of the Effects of Hypolimnetic Oxygenation on Lake and Reservoir Water Quality. *Lake Reservoir Mgt. 15(4):285-297.*

Bostrom, B., J.A. Anderson, S. Fleischer, and M. Jansson. 1988. Exchange of Phosphorus Across the Sediment-Water Interface. *Hydrobiol. 179:229-244.*

Cooke, G. D., E. Welsh, S. Peterson, and P. Newroth. 1993. *Restoration and Management of Lakes and Reservoirs*. Lewis Publishers. Boca Raton, FL. USA.

Funk, W.H. and B.C. Moore. 1988. *Newman Lake Restoration Feasibility Study*. State of Washington Water Research Center Report. Washington State University. Pullman, WA, USA.

Lorenzen M.W. and A. Fast. 1977. A Guide to Aeration/Circulation Techniques for Lake Management. USEPA 600/3-77-004.

McQueen, D.J, and D.R.S Lean. 1986. Hypolimnetic Aeration: An Overview. *Water Poll. J. Can. 21(2):205-217.*

Moore, B.C., P.H. Chen, W.H. fun, and D. Yonge. 1996. A Model for Predicting Sediment Oxygen Demand Following Hypolimnetic Aeration. *Water Res. Bull. 32(4):1-9.*

Nurnberg, G. 1995. Quantifying Anoxia in Lakes. *Limnol. Oceanorg. 40(6):1100-1111.*

Speece, R.E., M. Madrid, and K. Needham. 1971. Downflow Bubble Contact Aeration. *Am. Soc. Civ. Eng. Div. 97(SA4):433-441.*

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Section 3. Air as a Supplemental Oxygen Source

3.   Aeration Technology

I. Supplemental Aeration Characteristics

A. Selecting Tertiary Treatment Alternatives

After it has become evident that a more cost-effective solution than tertiary treatment is necessary for removal of a small increment of residual BOD in the treated wastewater, selecting the best oxygenation equipment available is advisable.

The objectives of oxygen supplementation to a harbor differ substantially from ordinary aeration of wastewater. The dissolved oxygen deficit in a harbor is about 4 mg per liter (8 – 4 mg/L), or about half of that found in wastewater treatment (9 – 1 mg/L). The 4 mg per liter dissolved oxygen level must be maintained even during the warmer temperatures in the summer, which reduce the air saturation concentration to 8.2 mg per liter, which constitute the critical seasonal conditions.

The cost of electricity has risen in many areas and must be factored into equipment selection. Since the unit energy consumption of conventional aeration is inversely proportional to the dissolved oxygen deficit driving force, a doubling of energy consumption will result if the D.O. deficit is halved, adding $60 to $120 per ton to the other costs of dissolved oxygen supplemented. At $0.06 per kilowatt hour and in water that has only 2 mg per liter of dissolved oxygen, 1000 to 2000 kWh per ton of dissolved oxygen is required.

Aeration technology utilizes various generic designs for dissolving oxygen from air into water such as surface aeration devices, coarse or fine bubble diffusers, Venturi aspirators and cascade/weir aeration equipment. Each of these systems can effectively dissolve oxygen from air into water if target D.O. in the water is low and the cost of electricity is minimal.

## B. Inherent Disadvantages of Aeration in Many Applications

Traditionally aeration technology was developed to meet the need to dissolve a large quantity of dissolved oxygen into wastewater to support the aerobic microbial metabolism of organic pollutants. Therefore the most commonly used aeration techniques were optimized for this purpose. However, it should be recalled that the systems were developed when electricity was still cheap, required bulk D.O. concentrations were 1 to 2 mg/L and compact aeration equipment was not necessary.

Air as a supplemental oxygen source has distinct disadvantages. Since air is composed of 79% nitrogen, the accompanying nitrogen gas can cause serious supersaturation problems if it comes into contact with water at above ambient pressure, which occurs in diffused aeration systems (not a problem with surface aerators). Nitrogen gas supersaturation can impair fish health, and even be lethal to them, (see a more extensive discussion later in this report).

Another disadvantage is that with the air as the oxygen source, if a discharge concentration of less than 5 mg per liter dissolved oxygen is produced by the aeration system, almost 100% of the harbor flow must be moved through the oxygenation system. Significant pumping and river diversion problems must then be addressed.

C. Historical Attempts to Use Surface Aerators for Supplemental Aeration

Shown in these photos are prototype installations which attempted to achieve supplemental aeration in shipping channels. They proved to be rather ineffective and quite energy intensive. The projects were abandoned.

Historical Applications of Surface Aeration for Oxygen Deficient Water Bodies
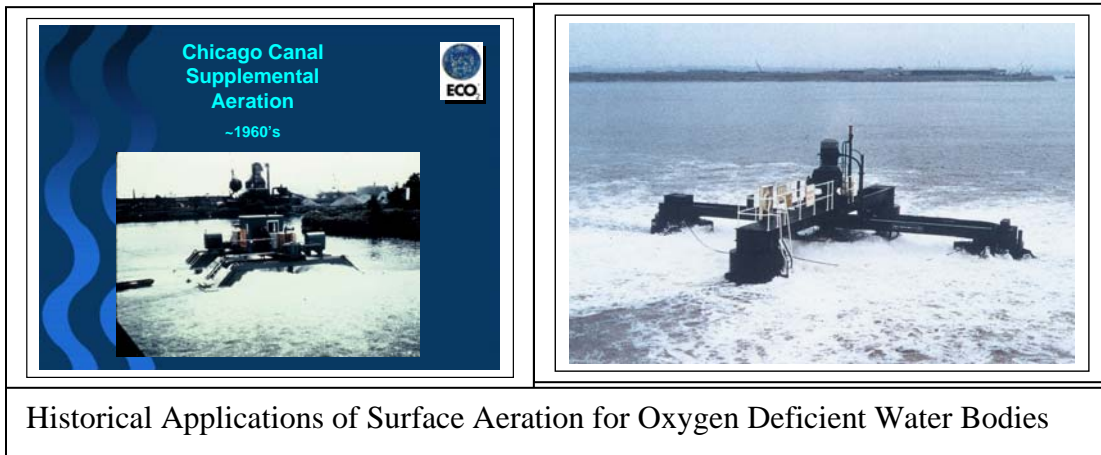
The following photos show the close spacing required of conventional surface aerators in wastewater treatment. This type of equipment placement is not appropriate for the Savannah Harbor shipping channel, which must remain unobstructed.
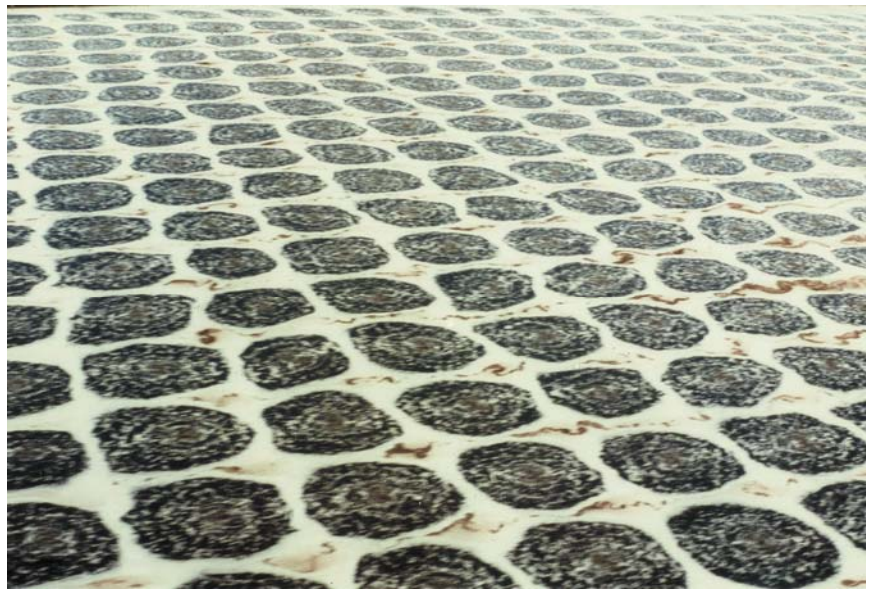
Conventional Aeration Systems Occupy Entire Volume of Aeration

II. Impact of Changing D.O. Requirements on Aeration Technology Applications
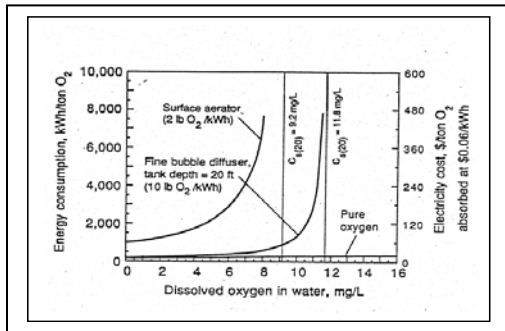
A. Aeration Technology Cost Effectiveness

Nowadays the increased cost of electricity has caused conventional aeration technology to become impractical if D.O. standards are set above 4 mg/L. Should dissolved oxygen standards for Savannah Harbor be raised in the future, many systems

may even be rendered obsolete. Table I indicates the approximate electricity consumption per ton of D.O. for surface aerators, coarse bubble diffusers or cascade weir aeration at 25 oC.

Table I. Unit Energy Consumption and Costs for Surface Aeration, Coarse Bubble and Cascade Weirs

D.O. (mg/L)	D.O. Deficit (mg/L)	# O2/kw-hr	kw-hr/ton D.O.	$0.05	$0.08	$0.11
				(Dollars/Ton of D.O.)		
0	8.2	2.6	770	38	62	85
1.2	7.0	2.0	1000	50	80	110
2	6.2	1.8	1100	55	88	120
3	5.2	1.5	1300	65	104	143
4	4.2	1.2	1700	85	136	187
5	3.2	0.9	2200	110	176	242
6	2.2	0.6	3300	165	264	363
7	1.2	0.35	5700	285	456	630

The waterfall height required to achieve indicated dissolved oxygen levels, along with attendant unit energy consumption at 25°C. Using cascade/weir aeration, is shown in Table II.

Table II. Height of Cascade Fall to Achieve Indicated D.O. Increase and Resultant Unit Energy Consumption

Change in D.O. (mg.L)	Required height -ft	kw-hr/ton of D.O. added
2 to 3	1.0	903
3 to 4	1.1	1070
4 to 5	1.4	1320
5 to 6	2.0	1890
6 to 7	4.0	3780
2 to 4	1.6	740
3 to 5	2.1	990
4 to 6	3.3	1560
5 to 7	8.1	3830
4 to 7	13.6	4290

Under the conditions described in Table III, superoxygenation becomes more cost effective than conventional aeration technology at 25 oC:

Table III Cost Effectiveness Criteria for Aeration and Oxygenation

Target D.O. mg/L	>5	>3	>1.2
Cost of electricity	$0.05	$0.08	$0.11

An example of the impact of higher D.O. standards and increased energy costs would be the beautiful Chicago Canal Cascade Aeration System (see photo) which already consumes unusually large amounts of electricity (3000 kwhr/ton D.O.) to meet the present low standard of only 3 to 4 mg/L. If higher dissolved oxygen standards are mandated, this system will have to be completely replaced with a more cost effective oxygenation system.
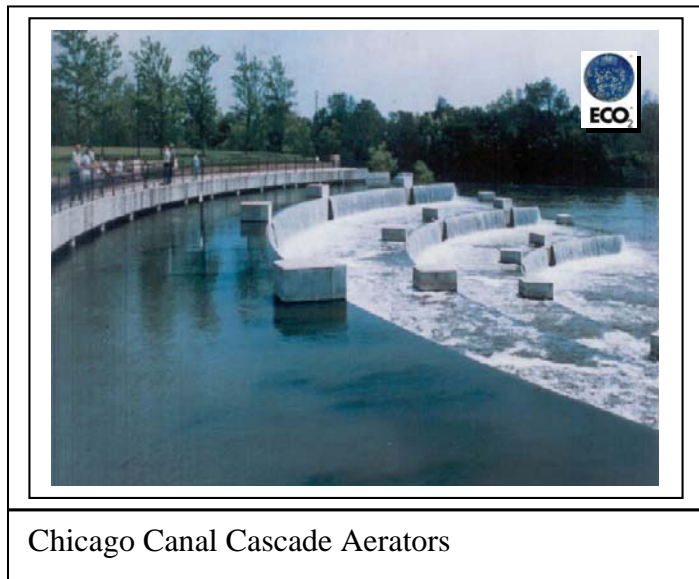
Chicago Canal Cascade Aerators

The following Figures... depict the performance characteristics of cascade/weir aerators. The upstream D. O. is related to downstream D. O as a function of fall height. The energy consumed by the pumps used in the process is shown for the various combinations of D. O. and fall height.

Weir aeration can be expressed as:

$$\text{Log } D_o = (0.815 \text{ Log } D_i - 0.385 \text{ Log height of fall}) ((1.024)^{T-20} + 0.062)$$

Fig 4. Relationship Between Downstream DO, Upstream DO and Fall at 30°C

Fig 7. Relationship Between Energy Consumption, Upstream DO and Fall at 30°C

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