SAVANNAH HARBOR REOXYGENATION DEMONSTRATION PROJECT

SAVANNAH, GEORGIA

Prepared for:

GEORGIA PORTS AUTHORITY

Savannah, Georgia

January 8, 2008

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Prepared by:

MACTEC ENGINEERING AND CONSULTING, INC.

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ACKNOWLEDGEMENTS

MACTEC Engineering and Consulting, Inc. (MACTEC) first approached the Georgia Ports Authority (GPA) about a Savannah Harbor reoxygenation (ReOx) demonstration design in late 2006. From these initial discussions, GPA director Doug Marchand was quick to recognize that a successful and timely ReOx demonstration in Savannah Harbor could directly prove the feasibility of large-scale dissolved-oxygen (DO) mitigation in support of GPA's critically-needed harbor-deepening expansion project. So rather than just a ReOx demonstration design as MACTEC had initially envisioned, GPA further challenged MACTEC to also assemble, operate, and monitor the envisioned ReOx demonstration system in time for the upcoming summer "critical season" of 2007. This was an exceptionally fast-track project from the outset and MACTEC deeply appreciates the trust and "can do" spirit that Doug Marchand and his Ports Authority team brought to all phases of the project.

We particularly want to recognize GPA's Hope Moorer, who made it possible to complete the demonstration project with such an accelerated schedule, and Dick Speece, inventor of the Speece Cone superoxygenation technology, whose wise counsel made it possible to quickly adapt the technology for full-scale application in such a large tidal system as Savannah Harbor.

MACTEC would also like to acknowledge the subcontractors and equipment suppliers who contributed to the work and participated to a major degree at one stage or another during the ReOx Demonstration Project as follows: Eco-Oxygen Technologies (ECO2), Savannah Marine Services, Georgia Power, Godwin Pumps, Air Liquide, The Industrial Company, YSI Instruments, and Pine Environmental. The individuals representing these companies contributed their time and, more importantly, their technical skills and knowledge without reservation and the successful and timely completion of the demonstration project is a direct result of their collective efforts.

In addition, MACTEC acknowledges the dedicated MACTEC employees who spent long hours on the harbor in the hot summer months to develop the documentation needed for this report.

ACRONYMS

cfs	cubic feet per second
DO	dissolved oxygen
DVD	Digital Versatile Disc
EPD	Georgia Environmental Protection Division
GPA	Georgia Ports Authority
gpm	gallons per minute
KITB	Kings Island Turning Basin
MG	million gallons
mg/L	milligrams per liter
O&M	operation and maintenance
ppd	pounds per day
ppt	part per thousand
QA/QC	quality assurance/quality control
ReOx	ReOxygenation
RM	River Mile
ROM	rough order of magnitude
SC DHEC	South Carolina Department of Health and Environmental Control
TMDL	Total Maximum Daily Load
USACE	U.S. Army Corps of Engineers, Savannah District
USEPA	U.S. Environmental Protection Agency Region IV
USGS	United States Geological Survey
YSI	Yellow Springs Instrument Company

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EXECUTIVE SUMMARY

Background

Modeling previously performed by the U.S. Army Corps of Engineers (USACE) indicated that proposed further deepening of Savannah Harbor would result in lost reaeration capacity and that the lost reaeration could be offset (i.e., mitigated) by the addition of approximately 20,000 pounds per day (ppd) of dissolved oxygen (DO) to the deepened harbor during the critical summer months. The 20,000 ppd figure is called the DO "mitigation amount", (TetraTech, 2007).

On March 23, 2007, MACTEC Engineering & Consulting, Inc. (MACTEC) was contracted by the Georgia Ports Authority (GPA) to conduct an accelerated full-scale demonstration of "Speece Cone" oxygenation technology in Savannah Harbor as possible DO mitigation in support of harbor deepening. A temporary re-oxygenation (ReOx) demonstration system was designed, assembled, and operated in the harbor for a 40-day test period beginning August 7, 2007and ending September 16, 2007. The Savannah Harbor ReOxygenation Demonstration Project was performed so that questions regarding the performance of the Speece Cone technology could be addressed. This report presents the ReOx demonstration project results and provides recommendations for permanent ReOx installations.

Project Goal

The goal of the ReOx demonstration project was to prove that the DO mitigation amount of 20,000 ppd could be added to the harbor during the summer critical season and that the resulting instream DO response could be determined through instream DO monitoring.

ReOx demonstration system configuration

The ReOx demonstration system consisted of two custom-built, 12-foot diameter ECO2 Speece Cones with river water supplied by four 400-horsepower water intake pumps mounted on a 110-foot barge temporarily moored at The Industrial Company waterfront property on Hutchinson Island (river mile [RM] 14.1). Electrical power for the water intake pumps was supplied from a temporary on-shore transformer and oxygen for the Speece Cones was supplied from a liquid oxygen storage tank located on land. Liquid oxygen was delivered to the storage tank by truck every 24 to 36 hours during the 40-day demonstration period.

Speece Cone operating principles

The two Speece Cones have a combined pure oxygen dissolution maximum design capacity of approximately 30,000 ppd. The nominal water-flow capacity for the pump configuration was about 15,000 gallons per minute (gpm) at a hydraulic head of 150 feet (in the center of the cones). In operation, water was continuously pumped from the river at a depth of about 10 feet and delivered under pressure to the small-diameter top of the Speece Cones where pure oxygen bubbles are added to the incoming water flow. As the water and oxygen bubble mixture is forced downward inside the expanding cross section of the cones, the downward force of the flowing water counteracts the natural buoyancy of the pure oxygen bubbles and, thereby, suspends an oxygen "bubble swarm" inside the cones. The extended bubble-swarm contact time with the down-flowing water results in superoxygenation of the water exiting the bottom of the cones. This superoxygenated flow from the Speece Cones was piped directly back to the river to a depth of about 30 feet and mixed in the river by tidal action, without benefit of a diffuser. Some effervescence of oxygen was evidenced at the water surface in the form of rising fine bubbles. Toward the end of the 40-day test period, additional coarse-bubble oxygen releases were episodically observed due to diminishing pump-flow capacity caused by the progression of intake-screen fouling.

Limited down time experienced

Over the 40-day demonstration period, the ReOx system operated for a total of 39 days. Down time was due to occasional equipment malfunction, running out of oxygen (twice), pump maintenance, and intake screen cleaning.

27,000 pounds per day of oxygen added to the harbor

A total of 1,272,080 pounds of oxygen was delivered and consumed over 39 days of ReOx system operation, giving an average oxygen consumption rate of 32,600 ppd. The overall transfer efficiency was 85 percent for the temporary demonstration system with some loss during tank filling, the average amount of oxygen added to the river was about 27,000 ppd. The oxygen concentration delivered from the cones to the river ranged from about 120 to 180 milligrams per liter (mg/L).

Instream monitoring to estimate DO improvement

Intensive instream DO monitoring was conducted before, during, and after the 40-day operating period in order to estimate the level of DO improvement resulting from operation of the ReOx demonstration system. Fixed-location continuous monitoring included shallow, middle, and deep zone multi-parameter recording instruments deployed at three near-shore locations: GPA Berth 20 dock at river mile (RM) 15.6, ReOx barge at RM 14.1, and USACE dock at RM 13.7. Periodic manual instream monitoring included repeated slack-tide longitudinal full-depth profiles at mid channel and cross-channel transects at five locations spaced along a three-mile river "target segment" centered on the ReOx barge location. Parameters measured or computed included: water temperature, DO concentration, DO saturation percentage, DO deficit, pH, conductivity, salinity, water density, and instrument depth.

Photosynthesis and respiration evident

The continuous near-shore monitoring results, at shallow and mid depth, often showed daily DO patterns indicative of light-driven photosynthesis and respiration with maximum DO concentrations occurring in the late afternoon and minimums occurring at dawn. This photosynthetic and respiration effect has no impact on the Speece Cone oxygen addition technology as long as instream DO concentrations at the shallow depth remain below saturation concentrations as was the case throughout the demonstration project.

ReOx system reduces target segment average DO deficit by 0.6 to 0.7 mg/L

Mid-channel low-tide longitudinal DO profiles show a target-segment average DO deficit (DO deficit is defined in Section 3.0, Page 3-1) of 3.9 mg/L just before the ReOx system began operation on August 7, 2007. After about one month of ReOx system operation, the average mid-channel low tide DO deficit was reduced to 3.3 mg/L and after the ReOx system had been shut down for about one week at the end of the 40-day demonstration period, the target segment low-tide DO deficit had returned back to the starting baseline deficit of 3.9 mg/L. This means that the ReOx system operation reduced the mid-channel average low tide DO deficit along the three-mile-long target segment by about 0.6 mg/L. Similarly, independent cross-channel transect monitoring at five locations along the target segment showed an average DO deficit reduction of about 0.7 mg/L during the ReOx demonstration period which compares favorably to the 0.6 mg/L DO deficit reduction determined from the longitudinal mid-channel profiles.

Delayed instream DO response a stabilizing benefit

Instream DO monitoring shows that it takes about three continuous days of oxygen addition to begin reducing mid-channel DO deficits and that some residual effects of oxygen addition remain locally evident near the ReOx barge for about one week after oxygen addition is ended. This delayed DO response is not unexpected for such a large and dispersive tidal system like Savannah Harbor and suggests that short interruptions of oxygen addition are not likely to cause an abrupt or significant DO decrease. This same dispersive nature of the harbor system might also be conducive to the timing of daily oxygen additions that coincide with off-peak electric power rates as a potential cost-savings measure.

Recommendations going forward

Overall, the 2007 ReOx demonstration project confirmed that the Speece Cone technology can effectively add the required DO mitigation amount to the harbor and reduce instream DO deficits during critical summer conditions. The demonstration also confirmed the soundness of the prototype design. We recommend the following actions:

- Develop a modular land-based ReOx station design specific to Savannah Harbor conditions, taking into account the "lessons learned" from the 2007 demonstration project.
- Identify, characterize, and acquire suitable shore locations for construction of two land-based dual cone ReOx stations.
- Obtain the necessary permits and approvals for construction and operation of the land-based ReOx stations.
- Construct the foundations and permanent shore-based infrastructure and service access for each ReOx station in advance and make the stations ready for subsequent seasonal installation and operation of the ReOx equipment in concert with harbor deepening.
- Until permanent land based ReOx systems are operational, temporary barge mounted systems could be used to provide oxygen for seasonal mitigation.

1.0 INTRODUCTION

The proposed deepening of Savannah Harbor is critically important to the Georgia Ports Authority (GPA) and the State of Georgia. Without deepening, the Port of Savannah and Georgia risk losing significant business and revenue to other east-coast ports that can accommodate the growing number of larger deep-draft ships. An aerial view of Savannah Harbor with river mile (RM) references is shown on Figure 1-1.

Harbor deepening will have the unintended consequence of reducing atmospheric reaeration into the harbor's deepened water. This reduced reaeration can result in reduced dissolved oxygen (DO) concentrations, particularly during the critical season from about mid June through mid October when river temperatures are higher and lower river flows are more prevalent. Three-dimensional hydrodynamic and water quality monitoring performed by the U.S. Environmental Protection Agency (USEPA) Region 4 and the U.S. Army Corps of Engineers, Savannah District (USACE) indicated that the proposed deepening of Savannah Harbor to 48 feet would result in lost reaeration capacity in the river that equates to a reduction of approximately 20,000 pounds per day in the river DO, (TetraTech, 2007).

The GPA contracted with MACTEC Engineering and Consulting, Inc. (MACTEC) to conduct the Savannah Harbor ReOxygenation (ReOx) Demonstration Project. The ReOx Project was performed to directly demonstrate the feasibility and effectiveness of pure oxygen injection technologies (specifically the Speece Cone) as a mitigation measure for the proposed deepening of the harbor. The ReOx Project was a full-scale temporary installation of the Speece Cone technology conducted in the summer of 2007. The ReOx demonstration system was designed and sized to provide sufficient quantities of oxygen to the harbor to mitigate the expected impacts to the DO levels attributed to the proposed harbor deepening.

As part of the ReOx project, MACTEC conducted extensive river water quality monitoring activities from June through September and evaluated various design features to assess performance of the ReOx system. This report summarizes the project activities and conclusions and presents conceptual design considerations for permanent ReOx systems in the harbor.

1.1 BACKGROUND

The mission of the Georgia Ports Authority is to develop, maintain, and operate ocean and inland river ports within Georgia; foster international trade and new industry for state and local communities; promote Georgia's agricultural, industrial and natural resources; and maintain the natural quality of the environment. The Savannah River and the Port of Savannah have long been influential in the economic development of Georgia. The Port of Savannah is the second largest container port on the East Coast and is the 4th largest container port in the nation. To maintain its place as a world class container port, the GPA approached the USACE regarding further expansion of the harbor by increasing the capacity of the navigation channel. As part of the federal authorization to deepen the channel, mitigation for environmental impacts from the proposed action must be implemented. Currently, the GPA and the USACE are conducting the Savannah Harbor Expansion Project. Results of the Savannah Harbor Expansion Project have provided assessments of the projected impacts and mitigation requirements for the proposed harbor deepening project. As part of its mission, the GPA is committed to completing environmental mitigation related to further expansion of the harbor, including the expected impacts to the reaeration capacity.

In 2005, MACTEC completed a feasibility level study for the USACE that identified and evaluated alternative techniques for improving DO concentrations in the harbor (MACTEC, 2005). Based on the MACTEC study, the USACE identified molecular oxygen injection using the Speece Cone technology as a cost effective technique to improve harbor DO.

In addition to the activities ongoing as part of the Savannah Harbor Expansion Project, the USEPA Region 4, the Georgia Department of Natural Resources, Environmental Protection Division (GA EPD), and the South Carolina Department of Health & Environmental Control (SC DHEC) are coordinating the development of new DO criteria for Savannah Harbor. The completion of this coordinated effort will result in the DO criteria being included in Georgia's Water Quality Standards. The quantity of oxygen added for mitigation of dredging is independent of the DO standard for the harbor because it is the quantity of additional dissolved oxygen needed to offset the predicted DO impacts of the proposed deepening.

1.1.1 SPEECE CONE OPERATING PRINCIPLES

The Speece Cones that were used were each capable of injecting up to 15,000 pounds per day (ppd) of oxygen. The estimate of the oxygen needed for DO mitigation associated with the proposed deepening is 20,000 ppd. The injection of this quantity requires the operation of at least two Speece Cones during summer critical conditions. The nominal water-flow capacity for the pump configuration that supplied water to the Speece Cone was about 15,000 gallons per minute (gpm) at a hydraulic head of 150 feet (in the center of the cones). In operation, water was continuously pumped from the river at a depth of about

10 feet and delivered under pressure to the small-diameter top of the Speece Cones where pure oxygen bubbles were added to the incoming water flow. As the water and oxygen bubble mixture is forced downward inside the expanding cross section of the cones, the downward force of the flowing water counteracts the natural buoyancy of the pure oxygen bubbles and, thereby, suspends an oxygen "bubble swarm" inside the cones. The extended bubble-swarm contact time with the down-flowing water results in superoxygenation of the water exiting the bottom of the cones (Figure 1-2). This superoxygenated flow from the Speece Cones was piped directly back to the river and discharged at a depth of about 30 feet where it was dispersed in the river by tidal action without benefit of a diffuser. Some effervescence of oxygen was evidenced at the water surface in the form of rising fine bubbles. Toward the end of the 40-day test period, additional coarse-bubble oxygen releases were episodically observed due to diminishing pump-flow capacity caused by the progression of intake-screen fouling.

1.1.2 ReOx SYSTEM DESIGN CONSIDERATIONS

The ReOx system was a temporary barge-mounted Speece Cone system capable of providing up to 30,000 ppd of oxygen using two separate Speece Cone systems and was assembled and demonstrated on an accelerated schedule. A barge-mounted ReOx system had several potential advantages that made this approach a good alternative for the GPA.

- Because oxygen addition is typically only a seasonal need (e.g., mid June through mid October), a flexible and modular barge-mounted ReOx system can potentially be dismantled into major components and removed to land storage during the off season, thereby making the barge available for other duty.
- A barge-mounted configuration substantially eliminates the need for landside disturbances. The only landside connection needed is a seasonal power-and-oxygen umbilical running from shore to the moored barge. There is no fixed intake or discharge pipe construction required because these assemblies are attached to the barge.
- A barge-mounted ReOx system can be positioned in the harbor to minimize potential navigation hazards and can be moved on fairly short notice to accommodate harbor emergencies such as approaching meteorological events.
- Obtaining permits and approvals for fabrication and operation of a floating barge-mounted seasonal system is less difficult and time consuming than obtaining the permits and approvals required for fixed land-based installations.
- The Speece Cones fabricated for a barge-mounted system can later be reused in a permanent land-based system.
- Design is easily expanded to meet additional oxygen requirements.
- Optionally, a barge mounted system design could be used until permanent land-based systems are constructed or as the permanent system design during the critical season.

2.0 DEMONSTRATION SYSTEM DESIGN

Because the ReOx demonstration system was a temporary installation, the original design concept incorporated the use of a barge as the base for the re-oxygenation station and the use of available rental equipment. It was determined that the test would require two Speece Cones each capable of transferring a maximum of 15,000 ppd, four 400 horsepower pumps, and a single liquid oxygen storage tank and vaporization system, Figure 2-1. The intake pipes leading to the pumps employed a screen to prevent foreign matter, including debris and fish, from being entrained in the system. The intake screens were mounted to the pipes approximately 8 feet below the water surface (top of the screen) and extended to approximately 12 feet below the water surface (bottom of screen) (Figure 2-2). The return pipes for the cones extended approximately 30 feet below the water surface (Figure 2-2) and were angled to direct the super-oxygenated water toward the center of the navigation channel in the river.

During the conceptual design stage, it was determined, due to the logistics of supply, safety, and environmental issues, that diesel powered pumps and generators were unsuitable. Therefore, electrical power was supplied from a stationary site on shore. Also, due to logistical considerations liquid oxygen converted from liquid to gas on shore, was supplied by use of an umbilical to the barge. Both of these elements were located at the temporary mooring site for the barge at river mile (RM) 14.1.

3.0 SYSTEM PERFORMANCE VERIFICATION

The ReOx system was operated from August 7 to September 16, 2007 and required a total of 1,272,080 lbs of oxygen (provided at the storage tank). This oxygen was dissolved into approximately 837 million gallons (MG) of river water that was reintroduced at a depth of 30 feet below the water surface. The amount of oxygen dissolved into the river system averaged 27,000 ppd over the 39 days of operation. The project demonstrated that it was possible to achieve the main project goal of reliably injecting a minimum of 20,000 ppd of oxygen into the Savannah Harbor system to offset the estimated DO impact from the proposed deepening.

To assess the amount of oxygen added to the river system three checks were in place: 1) A log was kept of the amount of oxygen that was supplied to the liquid oxygen storage tank; 2) Water quality meters (Yellow Springs Instrument Company [YSI] 6920 data sondes) were used to periodically measure a side stream sample of super-oxygenated water from the return pipes; and 3) A control panel attached to each cone recorded flow, temperature, pressure, and oxygen usage. In addition to the three oxygen usage checks, the intake river water DO concentration was also monitored.

As part of the evaluation of the performance of the Speece Cones, extensive instream water quality monitoring was conducted before, during, and after the demonstration period. In analyzing DO data sets for Savannah Harbor, there are many concurrent and variable influences on DO concentrations that can confound interpretation of DO monitoring results. Atmospheric oxygen is only sparingly soluble in water and the DO solubility limit, or DO saturation concentration, is a direct function of water temperature, salinity and barometric pressure for a water sample; colder water can hold more DO than warm water, fresh water can hold more DO than saline water, and all water can hold more atmospheric DO as barometric pressure increases.

The DO deficit is the difference between the calculated DO saturation concentration for the prevailing temperature, salinity, and barometric pressure and the directly measured DO concentration in a water sample. By normalizing the DO concentration data to DO deficit concentrations, the data are, thereby, automatically normalized for the direct and highly variable effects of changes in temperature, salinity, and barometric pressure. Therefore, changes in the DO deficit substantially reflect only those DO changes resulting from factors and processes other than changes in water temperature, salinity, and barometric pressure. For these reasons, changes in the instream DO deficit distributions are considered the single best direct indicator of oxygen addition results. Therefore, representative measurement of the DO deficit distribution in the target segment of the harbor is a key monitoring objective.

The two Speece Cones (Cone 1 and Cone 2) were turned on August 7 and turned off September 16, 2007. Cone 1 was shutdown for a total of 2 days, 5 hours, and 58 minutes for an effective operation of 37 days, 13 hours, and 9 minutes. The total amount of water pumped through Cone 1 during operations was 418 MG. Cone 2 was shutdown for a total of 21 hours and 54 minutes for a total effective operation of 39 days. The total amount of water pumped through Cone 2 during ReOx operations was 419 MG. Thus, the total amount of water pumped through the pump configuration for two cones was 837 MG. On average the ReOx system pumped at a rate of 15,000 gallons per minute. The demonstration project consumed 960,000 kWh. The energy usage cost approximately $89,000.

3.1 INFLUENT MONITORING

Continuous water quality monitoring was performed using the 6920 sondes. A sample of river water from the intake side of the cones was pumped to a monitoring station located on the barge deck. Monitoring of the influent began August 4, 2007, approximately three days before startup and continued until September 16, 2007, when the system was turned off. Influent water quality monitoring data are available in Appendix A Geodatabase referenced as Table Intake_Zone located on the Digital Versatile Disc (DVD) provided as part of this report.

Results from continuous monitoring of the intake water are shown in Figure 3-1. The water temperature intake data show a significant nighttime cooling effect on the Savannah River. Additionally, the data indicate that there was no significant short circuiting from the superoxygenated return flow to the intake. The intake DO deficit (daily average) was 3.4 milligrams per liter (mg/L) at startup on August 7, 2007. The smallest DO deficit (daily average) was observed on August 24, 2007 at 2.7 mg/L. During operations, the highest daily average DO deficit measured from the intake was on August 29, 2007 at 3.8 mg/L when the ReOx system was off for a brief time during the day for oxygen flow adjustments.

3.2 OXYGEN USAGE INFORMATION

A total of 1,272,080 pounds of oxygen was delivered and consumed over 39 days, from August 7 to September 16, 2007, of ReOx system operation, giving an average oxygen consumption rate of 32,600 ppd. The overall transfer efficiency was 85 percent for the temporary demonstration system with some loss during tank filling, the average amount of oxygen added to the river was about 27,000 ppd. The oxygen concentration delivered from the cones to the river ranged from about 120 to 180 milligrams per liter (mg/L). Return flow concentrations varied with flow rates through the cones.

3.3 SPEECE CONES DATA REPORTING

The control panel on each Speece Cone records oxygen flow rates entering the cone, the intake water flow rate, water temperature, and system pressure. These data are shown graphically on Figures 3-1 through 4-2 and the data are in Appendix A. Each cone was set to have a nominal oxygen flow of 15,000 ppd. During the ReOx system operation, it was noted that Cone 2 was not performing similar to Cone 1. The oxygen flow valve on Cone 2 (31 percent) was opened significantly less than Cone 1 (46 percent) and fewer bubbles were noted in the view ports on Cone 2. Discussions with the Speece Cone representatives concluded that the oxygen flow meter on Cone 2 was likely mis-calibrated and that the oxygen flow in Cone 2 was too low previously. Therefore, after several oxygen flow ramp-up tests on August 29 and August 30, 2007 were conducted, an appropriate setting for the percent open for the oxygen flow valve for Cone 2 was determined. Once completed, the oxygen flow range setting on the control panel was adjusted to represent a set oxygen flow of 15,000 ppd for Cone 2. Both flow meters (Cones 1 and 2) were returned to the manufacturer after completion of the demonstration project and recalibrated so that they can be reinstalled when the cones are redeployed at a later date.

3.4 SYSTEM PERFORMANCE

Water Intake System Performance

Biological growth, recognized as several species of hydroid (Class Hydrozoa), began to accumulate on the intake screens. The amount of biological growth on the intake screens was not anticipated by MACTEC or the screen manufacturers who had experience in the conditions in the harbor. Cleaning of the exterior of each intake screen box was performed twice by a diver. However, no contingencies were made for cleaning the interior of the intake screen boxes. Therefore, there was notable progressive head loss in the pumping system, primarily in Cone 2. As part of the observations of the demonstration project, regular cleaning or replacement of the screens must be part of the design and operations of permanent systems. Photographs of the intake screens before and after the demonstration period may be found in Figure 3-2.

Maintenance was performed on the pumps approximately every 250 hours of operation. The system was turned off for maintenance on August 16, August 27, and September 6, 2007. In the beginning, the maintenance was performed one cone at a time thus the pumps for only one cone would be off at a time. Once it became necessary for a diver to remove biological growth from the intake screens, it was decided to shut down both systems during pump maintenance due to diver safety concerns.

Oxygen Delivery to Cones

During routine oxygen tank refills the pressure would drop in the liquid oxygen storage tank and result in a temporary loss of pressure in the oxygen supply lines. This pressure drop could result in system shutdown. By working with the liquid oxygen supply company it was possible to minimize occurrences of this problem. Also, the control panel settings were initially set to shut the system down when a change of 200 ppd of oxygen flow was detected. An oxygen flow drop of this magnitude would occur during the filling of the storage tank. Because it was more important to maintain system flow, the alarm/shutdown setting was adjusted to allow a maximum change of 1,000 ppd of oxygen before an automatic shutdown. Additional adjustments of the appropriate set points for the alarm system would be needed for permanent installations. Approximately 32,600 ppd of liquid oxygen were delivered to the liquid oxygen storage tank. Spot checks of oxygen concentrations in the discharge line showed concentrations from approximately 120 mg/L to 180 mg/L.

4.0 RIVER MONITORING

Various activities were going on during the demonstration project. The activities that occurred during the ReOx system demonstration period are shown on a timeline of events prepared as Figure 4-1. Events noted included USACE dredging schedule and system operations.

During the ReOx Demonstration Project water quality monitoring was conducted by MACTEC at three stationary near-bank locations (at GPA Berth 20 (RM 15.6), at the barge location (RM 14.1), and the USACE Dock (RM 13.7) shown in Figure 4-2. In addition to the stationary monitoring locations, periodic monitoring along mid-channel profiles (Figure-4-3, 4-3.1, and 4-3.2) including extended long run monitoring to the KITB (RM 19) and five cross-channel transects was conducted during low and high tide events (Figures 4-4, 4-4.1 and 4-4.2. Water quality parameters measured, or calculated from primary measurements, included: water temperature, DO, DO percent saturation, DO deficit, salinity, conductivity, pH, density, and instrument depth. Sampling locations for the periodic measurements are shown on Figures 4-3 and 4-4. Long run monitoring locations are shown on Figure 4-5.

Water quality monitoring was conducted to assess instream conditions before, during, and one week after the 40-day ReOx project demonstration period. At both the stationary locations and periodic locations, YSI 6290 multi-parameter sondes were used to monitor water quality parameters. Instrument calibration and maintenance was conducted in accordance with the manufacturer's instructions and the procedures specified in the Monitoring Plan in Appendix B. Additional instrument calibration checks were performed as site conditions dictated. Calibration data were recorded and filed with the project field records and may be found in Appendix A, Geodatabase. At the beginning and end of each sampling event, equipment was inspected for damage, or faulty parts, and problems reported to the monitoring team leader. The monitoring team leader was responsible for equipment, its repair status, and ordering of parts.

For the periodic monitoring events, quality control grab samples were taken at monitoring locations using a Kemmerer type water sampler to collect a corresponding DO sample for comparison with the water quality monitoring instrument (YSI 6920 sondes). This grab sample is taken to the field laboratory for testing using the EPA approved Winkler method. DO grab samples were fixed in the field and returned to the field laboratory for DO titration (Hach Water Analysis Handbook, 2003). Data from the Winkler titrations were used as a quality assurance/quality control (QA/QC) check of the field instrument measurements. A minimum of ten percent (10 percent) of the discrete monitoring points in the river had QA/QC water samples collected. The measurement of these "field duplicate samples" met the measure of precision necessary to maintain and follow the quality control protocols for this water quality monitoring specified in the Savannah Harbor ReOxygenation Water Quality Monitoring Plan (Appendix B).

4.1 DREDGING ACTIVITIES

Dredging disturbs sediments on the bottom of the river and some are released to the water column. Such sediments generally contain an organic component that may cause an increased oxygen demand in the water column as dredging is under way. Therefore, dredging in the harbor is limited to times when the DO of the river is greater than 3 mg/L. Generally, dredging activities occur less during the summer when water temperatures are higher and DO concentrations are lower. When MACTEC activated the stationary background water quality monitoring stations on July 9, 2007, USACE dredging was occurring near the Marsh Island Turning Basin and this dredging continued until August 24, 2007. The USACE dredging began in the King's Island Turning Basin (KITB) on August 25 and continued through September 30, 2007, at several locations well after the ReOx system shutdown on September 16, 2007. The USACE measured water quality in the harbor during dredging operations. These USACE data are tabulated in Appendix C.

MACTEC was notified on August 25 that a break in the USACE dredge line had occurred. Increased sediment in the on-deck monitoring system at the ReOx barge location was noted from August 21 to August 24, 2007. The break in the dredge line released high concentrations of sediment to the water column. This high sediment load likely resulted in increased oxygen demand in the river system.

4.2 MONITORING AT STATIONARY LOCATIONS

Eighteen water quality sondes were deployed at the near-shore stationary monitoring stations (GPA Berth 20, the barge location, and the USACE Dock). Six sondes were used at each location. Sondes were placed in pairs (designated as primary and secondary) at selected depths (approximately 1 meter below the surface, near mid depth, and 1 meter from the bottom) to continuously monitor water quality (DO concentration, DO percent saturation, water temperature, conductivity, salinity, and depth). Each sonde was set to record water quality data at 15 minute intervals. The monitoring data collected at these stationary locations are available in electronic format in the Geodatabase (Appendix A) on the attached DVD. These data have been subjected to the appropriate QA/QC checks.

Due to the volume of the data collected, the data are summarized in graphical displays. Figure 4-2 (multiple figures for each stationary location) presents the continuous near-shore monitoring series:

- Figure 4-2.1 is based on data collected upstream from the ReOx system (at GPA Berth 20, RM 15.6);
- Figure 4-2.2 is based on data collected at the ReOx barge location, (RM 14.1); and
- Figure 4-2.3 is based on data collected downstream from the ReOx system (at the USACE Dock, RM 13.7).

The secondary sondes were deployed at each location and depth to duplicate the primary sonde readings in order to reduce the potential for data gaps resulting from instrument problems. Personnel checked on the sondes remotely (via internet) and visited the deployment locations approximately once per week to replace the sondes (one set at a time – primary or secondary) with recalibrated instrumentation. Sondes removed from a site underwent a calibration check (to check for potential instrument drift), data collection (downloaded from the memory of the sonde), cleaning, maintenance as needed, and were recalibrated prior to redeployment at a new location.

Monitoring Procedures

The reference standards for field instrument calibration are described in the monitoring plan (Appendix B). If there was evidence of fouling on the sondes or notable drift in the data, then the sondes were changed out more often than required by the standards. To allow for uninterrupted data monitoring, scheduling for the change out and recalibration of the sondes was such that a continuous monitoring sonde and its associated duplicate were not being changed at the same time. Calibration of the sondes was in accordance with the manufacturer's specification and the guidelines that are outlined for instrument calibration in the monitoring plan, Appendix B.

Findings From Stationary Locations

Monitoring data from the stationary locations show a noticeable diurnal pattern of the DO concentration. These diurnal DO swings are particularly noticeable on the shallow series data for each stationary location as shown in the Figure 4-2 series. This diurnal swing, not as notable in the mid or deep data, is likely caused by photosynthetic activity in the upper layers of the water column. Also observed are fairly stable and higher water temperatures prior to August 24, 2007 and a cooling trend afterward. This indicates that the ocean boundary cooled and produced higher oxygen concentrations (lower DO deficits) near the ocean and during high tides.

Upstream of the ReOx system (at GPA Berth 20, RM 15.6):

The GPA Berth 20 monitoring station was approximately 1.5 miles upstream from the ReOx system. The station was attached to the Berth 20 dock located on the right side of water (city side). It was necessary to locate the continuous monitoring stations on fixed structures in the harbor and out of the navigation channel; therefore, the placement was not ideal to monitor the effects of the ReOx system in the navigation channel.

Prior to startup on August 6, 2007 the DO deficit was 3.7 mg/L (shallow zone), 4.0 mg/L (middle zone), and 4.2 mg/L (deep zone). Within 48 hours the average DO deficit was improved (decreased) at the GPA monitoring location (1.5 miles upstream from the ReOx system) by about 0.1 mg/L. After 4 days of reoxygenation the average DO deficit was improved by 0.4 mg/L. These comparisons use the daily average DO.

GPA (RM 15.6)	Prior to ReOx System Startup	Elapsed time after ReOx system startup			
	8/6/2007 DO deficit (mg/L)	48-hour DO deficit (mg/L)	48-hour DO Deficit improvement (mg/L)	4-day DO deficit (mg/L)	4-day DO deficit Improvement (mg/L)
Shallow zone	3.7	3.6	0.1	3.3	0.4
Middle zone	4.0	3.9	0.1	3.6	0.5
Deep zone	4.2	4.1	0.1	3.9	0.3

Prepared By: TRK 11/19/07
Checked By: LMS 11/19/07

After running for about 10 days straight, the ReOx system was turned off for operations and maintenance (O&M) on August 16, 2007. At shutdown the DO deficit was 3.4 mg/L (shallow zone), 3.7 mg/L (middle zone), and 3.9 mg/L (deep zone). The ReOx system was reactivated on August 17, 2007. Forty-eight hours after restarting the ReOx system the average DO deficit across the water column at the GPA location was improved by 0.5 mg/L.

GPA (RM 15.6)	**System shutdown**	**While system was off**	**Elapsed time after ReOx system restart**	
	8/16/07 DO Deficit (mg/L)	**8/18/2007 DO deficit (mg/L)**	**8/20/07 DO deficit (mg/L)**	**4-day DO Deficit improvement (mg/L)**
Shallow zone	3.4	2.9	2.5	0.9
Middle zone	3.7	3.6	3.3	0.4
Deep zone	3.9	4.0	3.7	0.2

Prepared By: TRK 11/19/07
Checked By: LMS 11/19/07

On the day of final system shutdown (9/16/07), the DO deficit at the GPA monitoring location was 3.1 mg/L (shallow zone), 3.4 mg/L (middle zone), and 3.6 mg/L (deep zone). Eight days after the ReOx system was shutdown, the DO deficit averaged 3.6 mg/L in the water column which was significantly less than the 40 day earlier DO deficit average of 4.0 mg/L in the water column. This decrease in DO deficit is attributed to the influence of cooler ocean water with lower DO deficits during high tides.

At the ReOx system location, (Barge, RM 14.1):

Prior to startup on August 6, 2007 the DO deficit was 3.9 mg/L (middle zone) and 4.0 mg/L (deep zone). After 48 hours the DO deficit was improved at the ReOx monitoring location by 0.3 mg/L in the middle zone and 0.2 mg/L in the deep zone. After 7 days the ReOx system had improved the DO deficit by 0.5 mg/L in the middle zone and 0.6 mg/L in the deep zone.

After running for about 10 days straight, the ReOx system was turned off for O&M on August 16, 2007 at which time the DO deficit was 3.3 mg/L (shallow zone), 3.3 mg/L (middle zone), and 3.5 mg/L (deep zone).

On the day of final shutdown (9/16/07), the DO deficit at the ReOx barge location was 3.0 mg/L (middle zone) and 3.2 mg/L (deep zone). Eight days after shutting the system down, the DO deficit was still less than it was prior to startup conditions.

ReOx System (RM 14.1)	Prior to ReOx System Startup	Elapsed time after ReOx system startup			
	8/6/2007 DO deficit (mg/L)	48-hour DO deficit (mg/L)	7-day DO deficit (mg/L)	14-day DO deficit (mg/L)	9/16/07 Shutdown deficit (mg/L)
Shallow zone	No data	3.7	3.4	2.4	No data
Middle zone	3.9	3.6	3.4	3.0	3.0
Deep zone	4.0	3.8	3.5	3.3	3.2

Prepared By: TRK 11/19/07
Checked By: LMS 11/19/07

The minimum DO deficits at the ReOx barge location were observed between September 12 and September 14, 2007. The deep zone had a DO deficit of 2.9 mg/L on September 12, 2007 began and the shallow and middle zone had a DO deficit of 2.3 mg/L and 2.8 mg/L respectively, on September 14, 2007, some 38 days after ReOx injection began.

Downstream of ReOx system (at the USACE Dock, RM 13.7):

Just prior to ReOx system startup the water temperature was rising and the DO deficit at the USACE dock was 3.7 mg/L in the middle zone and 3.8 mg/L in the deep zone. Approximately 24 hours later, after the system began operating, the DO deficit had decreased by 0.2 mg/L in both the middle and deep zones.

The ReOx system was shut down on August 18, 2007 for O&M. The water column average DO deficit was reduced by 0.3 mg/L about 24 hours after the system resumed normal operation on August 19, 2007 when water temperatures remained relatively constant. Forty-eight hours after operations were resumed August 20, 2007, the middle zone DO deficit daily average was 2.6 mg/L which was the best improvement noted during the demonstration project from the initial 3.7 mg/L DO deficit on August 6, 2007, thus the deficit was reduced by 1.1 mg/L. The best observed DO deficit daily average for the shallow zone was on August 22, 2007 at 2.4 mg/L and the minimum deficit for the deep zone was on August 24, 2007 at a deficit of 2.9 mg/L.

The system was operating at a steady rate on September 12, 2007, four days before shutdown, with the DO deficit daily water column average of 2.9 mg/L, which is similar to the water column four days after shutdown.

USACE Dock (RM 13.7)	**Prior to ReOx System Startup**	**Elapsed time since ReOx system startup**			
	8/6/2007 DO deficit (mg/L)	**14 Day DO deficit (mg/L) 8/20/07**	**1 day after Shutdown DO deficit (mg/L)**	**4 days after Shutdown DO Deficit (mg/L)**	**8 days after Shutdown DO Deficit (mg/L)**
Shallow zone	No data	2.5	3.1	2.7	3.3
Middle zone	3.7	2.6	3.3	2.9	3.5
Deep zone	3.8	2.9	3.2	2.8	3.4

Prepared By: TRK 11/19/07
Checked By: LMS 11/19/07

4.3 MONITORING ALONG MID-CHANNEL

Water quality sampling in the middle of the navigation channel was performed periodically (at least weekly) at 14 locations, V1 – V14, which extended from GPA Berth 20 to the USACE Dock (Figure 4-3). Due to the strength of the tides and the need to sample during slack tide conditions, the sampling was performed in a 2 to 3 hour window centered on a high or low slack tide.

Sampling locations were monitored using the hand held YSI 6920 sondes. These mid-channel DO measurements were taken at four (4) depths: 3 feet below water surface; 1/3 of total depth; 2/3 of total depth; and 3 feet above bottom. At the request of EPD, MACTEC assessed the potential for conducting more detailed water column measurements at 1-foot intervals for the top 10 feet and 2-foot intervals to the bottom. Since the mid-channel depths ranged from 48 feet (low tide) to 55 feet (high tide), the total number of measurements at one point would have been as high as 32 discrete measurements. Since it took a minimum of two to three minutes for the instrument to stabilize, the total time for measurement of one location approached one and a half hours. Since there were 14 sampling locations and it was important to keep the measurement period as short as possible so that the data were obtained under similar conditions and to avoid high currents (maximum time three hours per event), this methodology was not feasible, within available resources, for the periodic river sampling events.

The pH, specific conductivity, salinity, and DO instrumentation were calibrated prior to deployment and the calibration was checked after completion of the sampling event.

4.3.1 Mid-Channel Findings – DO Deficit

Table 4-1 summarizes the grid averaged DO deficit calculations. The grid average is the average DO deficit of the water column. The following details the Figures 4-3 s mid-channel isopleths.

Figure 4-3.1 a-b – Mid-Channel Monitoring DO Deficit at Low Tide
Figure 4-3.1 c-d – Mid-Channel Monitoring DO Deficit at High Tide
Figure 4-3.1 e-f – Mid-Channel Monitoring DO Concentration at Low Tide
Figure 4-3.1 g-h – Mid-Channel Monitoring DO Concentration at High Tide
Figure 4-3.1 i-j – Mid-Channel Monitoring DO Percent Saturation at Low Tide
Figure 4-3.1 k-l – Mid-Channel Monitoring DO Percent Saturation at High Tide

Low Tide Events

The results from the mid-channel monitoring events at low tide indicated that the improvement from August 6, 2007 to September 7, 2007 of the grid average DO deficit from the operation of the ReOx system was approximately 0.6 mg/L. The mid-channel low-tide monitoring event that occurred just prior to system startup indicated that the three-mile river segment being monitored had a grid average DO deficit of 3.9 mg/L. Once the effects of the ReOx system operation stabilized, on August 20, 2007, the grid average DO deficit after 13 days of reoxygenation was 3.3 mg/L, thus the DO deficit was improved by 0.6 mg/L. The average DO deficit based on all five low tide event grid averages was 3.4 mg/L, a DO deficit improvement of 0.5 mg/L, though after August 24, 2007 a cooling trend began to occur in the water temperature, which meant the stabilized condition on August 20, 2007 was more representative of the ReOx system effect during critical conditions than the period of time when the cooling trend began. The final monitoring event for the 3-mile segment 10 days post system shutdown indicated that the average DO deficit at low tide had returned to 3.9 mg/L, thus the effects of the system lasted for days after the system shut down.

These mid channel monitoring locations act as “snapshots” of the water quality profiles along the three-mile long target segment of the river centered on the ReOx barge location. Figure 4-3.1 graphically presents the low tide sampling results for all events.

High Tide Events

At mid-channel high tide improvement in DO was observed but was not as predominant and clear as the low tide measurements. Table 4-1 summarizes the grid average DO deficit calculations. Figures 4-3.2 present the high tide events. Prior to startup a DO deficit of 3.9 mg/L was observed a few weeks prior to startup during fairly steady critical conditions of high temperatures and low water flows. A week after the startup of the ReOx system, the DO deficit had been improved by 0.7 mg/L from July 16, 2007 to August 27, 2007. The average DO deficit from two high tide events during stable water temperature conditions was 3.2 mg/L. After August 24, 2007, the high tide deficits continued to further naturally decrease as a result of cooling sea temperatures and lower DO deficits.

4.3.2 Other Water Quality Data Findings

Mid-channel data for pH, salinity, and temperature are presented in a low and high tide series on Figures 4-3.2 as detailed below.

Figure 4-3.2 a-b – Mid-Channel Monitoring pH at Low Tide
Figure 4-3.2 c-d – Mid-Channel Monitoring pH at High Tide
Figure 4-3.2 e-f – Mid-Channel Monitoring Salinity at Low Tide
Figure 4-3.2 g-h – Mid-Channel Monitoring Salinity at High Tide
Figure 4-3.2 i-j – Mid-Channel Monitoring Temperature at Low Tide
Figure 4-3.2 i-j – Mid-Channel Monitoring Temperature at High Tide

Low Tide Events

During low tide conditions, the pH in the river is relatively neutral and is slightly greater at the bottom of the river. Salinity tends to have a low surface salinity and gradually increases with depth. The salinity ranges from approximately 6 parts per thousand (ppt) at the surface to 16 ppt at the bottom of the river. The temperature trends are very apparent on the Figure 4-3.2i-j; hotter temperatures appear red to yellow and cooler temperature appear green or blue.

At low tide the river was stratified through the first several weeks of monitoring (7/9/07 through 9/4/07). Salinity in the river was highest around August 20, 2007; this date 4900 cubic feet per second was observed (Figure 4-8.2) as a period of low flow as measured at the U.S. Geological Survey (USGS) Gage 02198500 near Clyo, GA. Water temperature was also highest during this same time. Figure 4-3.2 shows effects of the ReOx project on the river temperatures on August 20, 2007. This gradient effect was likely due to the lower river flows (as measured at the USGS Gage near Clyo, Georgia) and the fact that the intakes were located at the edge of water near the surface where water temperatures were warmer, particularly during daylight hours.

High Tide Events

Generally, high tide conditions brought a higher pH water into the harbor. The highest pH values occurred at the bottom of the river. Salinity at high tide conditions have a similar gradient as at low tide events, low values at the surface and higher at the bottom. However, a much higher salinity values are observed at high tide throughout the water column. Water temperatures during high tide events are generally cooler than during low tide events.

4.3.3 Long River Run Monitoring (RM 4 to RM 19)

In addition to the three-mile target segment in the vicinity of the ReOx system, monitoring over a 15 mile segment was also conducted. These “long run” monitoring events extended from approximately RM 4 to RM 19 as included at the end of Figure 4-3.1. Shortly after the ReOx system had been turned on, the USACE noticed an increased DO level at their KITB monitoring location approximately eight miles up river from the ReOx system location. After reviewing the data, it became apparent that long run monitoring would be helpful to assess a larger scope of the influence of the ReOx demonstration project. Beginning the week of September 6 to September 25, 2007, long run monitoring was completed weekly in Savannah Harbor. This was accomplished by beginning at RM 4 off Long Island upstream of Fort Pulaski and conducting a vertical profile (3 depths) every half mile until reaching RM 19 at the KITB (Figure 4-5). Profile readings were taken at shallow, middle, and deep depths. Long run results may be found in Appendix A, Geodatabase, Table Additional_Sampling_Water_Quality_Data.

Results from the long run monitoring indicated that DO levels were higher near the ocean and that the three-mile target segment under study for the ReOx Demonstration Project (USACE Dock to GPA Berth 20) was the critical segment identified in the TMDL report (USEPA, 2004). Also, data revealed that the KITB appeared to act as a storage location for higher DO water. As the flood tide moved upstream, the higher DO water from the ReOx system filled the KITB. As the tide moved out, the higher DO water was released and flowed downriver. A subset of the long run data (from RM 13 to RM 16) was incorporated in the mid-channel “target zone” series depicted on Figure 4-3. The long run monitoring data was collected on September 6, 7, 13, 19, and 25, 2007 and referenced as "Long Run" on the Figure 4-3.1 low and high tide series.

4.4 CROSS SECTIONS

Water quality was measured at five cross-section transects (at Berth 20, upstream of the Talmadge Bridge, the barge location, the convention center, and the USACE Dock) were measured (Figure 4-4). Figure 4-4.1 shows transect sampling points as follows:

- Overbank (river left facing downstream at A1 and A2)
- Channel toe (river left facing downstream at B1 through B3)
- Mid-channel (T1 through T5 readings at C1 through C4)
- Channel toe (river right facing downstream at D1 through D3)
- Overbank (river right facing downstream at E1 and E2)

These cross section transects act as slack tide "snapshots" of water quality within the ReOx demonstration target zone. Figures 4-4.2 depicts the low and high tide transects monitoring results for all events.

As with the periodic mid-channel sampling events, the cross section monitoring events were timed to coincide with local slack tide conditions (low or high). The pH, specific conductivity, salinity and DO instrumentation were calibrated prior to sonde deployment and checked at the completion of the sampling event.

Cross-Section Monitoring Findings

Table 4-2 shows the average DO deficit within each cross section and for all five cross sections for each tidal event.

The cross check between the mid-channel readings and the cross section readings are quite similar. The low-tide cross section point averaged DO deficit prior to ReOx injection was 3.9 mg/L. The cross section transects DO deficit at low tide was reduced from 3.9 mg/L to 3.0 mg/L after 14 days of ReOx system operation. During relatively stable river water temperatures between 8/10/2007 and 8/21/2007 the average DO deficit was 3.3 mg/L. This indicates that the DO deficit improvement was 0.6 mg/L.

4.5 NEAR BARGE MONITORING

Additional river monitoring included near barge monitoring shown on Figure 4-4 during the demonstration period to evaluate the local instream extent of notably supersaturated water from the ReOx system. Near-barge monitoring included taking profile readings at locations (S0A– 4A, S0B-S2B, S0C – S2C) adjacent to the barge on the day of ReOx system start up, August 7, 2007. Monitoring was completed in the center of the return line flow on the river side of the barge as shown in Figure 4-5.1. Readings were taken from a radius of 25 feet to 100 feet surrounding the barge at shallow, middle, and deep readings. As shown on Figure 4-5.1, the reoxygenated water dispersed quickly into the river and no extreme initial gradients were observed. The near barge monitoring consisted of 33 points taken on the day of the ReOx system startup, which averaged a 46 percent DO percent saturation, 3.4 mg/L DO concentration, and a DO deficit of 3.8 mg/L. This DO deficit at startup is consistent with the 3.9 mg/L measured in the mid-channel and cross section transects data sets.

As observed during the demonstration project, some effervescence was occurring, particularly as noted during slack tide conditions (Figure 4-6). This effervescence was attributed to turbulence occurring around the gate valves that controlled system pressure and flow at the discharge end of the ReOx system return lines. The gate valves were closed about 80 percent to create sufficient pressure in the cones. Effervescence was not noticed at mid-tide conditions because there was substantially more mixing of the water as a result of tidal flow in the river for mixing. Estimates from Dr. Richard Speece indicated that the oxygen lost to effervescence was likely much less than five percent of the total oxygen input. During near-barge monitoring several readings were taken in the center of the noted effervescence bubbles to assess DO concentrations; the highest DO concentration measurement was 4.3 mg/L. A permanent system design may utilize valves with a smoother transition and a multiport diffuser to further limit the potential for effervescence.

4.6 QA/QC REVIEW

For the ReOx Demonstration Project, MACTEC achieved a greater than 98 percent data recovery. The field monitoring data collected from the continuous monitoring stations and weekly sampling stations are stored in a non-relational database in Appendix A, Geodatabase. These data were reviewed by MACTEC so that the necessary parameters, measurements, and analytical results were properly recorded; the analytical results were evaluated for completeness and accuracy and suspected errors were investigated and resolved, as possible.

Data from the YSI 6290 sondes were considered valid if the post deployment calibration check did not deviate from pre-deployment calibration by more than ten percent. Data from sondes that did deviate by more than 10 percent were considered outliers and the corresponding measurement from the duplicate sondes were used to fill such data gaps.

In addition, during sonde deployment at the USACE dock it was noted that tidal/wave actions were causing the sondes to bounce on the support bolt in the sonde standpipes. This caused damage to the sonde batteries resulting in some data loss before this problem was identified and rectified. Data lost includes:

- Stationary Monitoring Location USACE-Mid (8/11 5:45pm to 8/13 4:00 pm), (8/24 11:00am to 8/27 3:00pm), and USACEM (9/15 11:30am to 9/16 2:00pm);
- Stationary Monitoring Location USACE-Deep (7/30 9:30am to 8/1 4:30pm) and (8/24 11:30am to 8/27 2:30pm)

Additionally, there were occasional events where data was lost due to the following: a floating surface sonde was caught by river debris and restrained at depth or by the support rope and came out of the water during low tides; at The Industrial Company due to available location for sonde placement prior to the barge setup that resulted in sondes being out of the water; and the monitoring station on the barge coming loose from the supports as a result of a boat collision.

Data Quality Objectives

The data quality objective for the ReOx project was to obtain sufficient and credible data that would support, with a reasonable level of certainty, that the monitoring results are correct. The quality controls for the ReOx project included assessing the precision, representativeness, comparability, and accuracy of the monitored parameter values, with particular emphasis on changes in DO deficit concentrations. See Appendix B, Savannah Harbor ReOxygenation Water Quality Monitoring Plan, for more detail on the data quality objectives. These data quality objectives were met for the project and a greater than 98 percent data recovery for all data collected by MACTEC was achieved.

4.7 DYE TEST OBSERVATIONS

A dye test was conducted near the end of the operation period to assess the dispersion characteristics of the superoxygenated water in the river. This test was planned as a qualitative observation of the behavior of the dye as it was released in the return lines. The dye test on September 12, 2007, was conducted at low slack conditions and as the river started flowing upriver toward the Kings Island Turning Basin. At approximately 17:05 hours on September 12, 2007, 55 gallons of permailon blue dye was injected into the ReOx system. Observations were made of the visible dye movement in the river.

Photograph log:

- Digital photographs were taken during the test every minute for the first 10 minutes and every 5 minutes thereafter until the dye had dispersed.
- Photographs were taken from the following locations during the dye test:
    - Barge location
    - Hyatt Hotel (located on River Street directly across the river)
    - Talmadge Bridge (upstream of the barge)
    - Boat

Visual observations did not note substantial quantities of dye at the surface of the river; this indicated that the superoxygenated return flow was entrained at deeper depths. There was some drag up of dye from the effervescence but the color noted indicated a large dilution of dye injected. To compare the injected dye color noted at the surface to the potential color if the flow had short-circuited to the surface, five gallons of dye were released from a boat to the surface of the river. Figure 4-7 shows the comparison of the deep dye injection versus the surface dye release.

In addition to field observations, water samples taken with a Kemmerer type sampler were also collected at 1 foot, 10 feet, 20 feet, 30 feet, and 40 feet below the river surface and placed in glass sample bottles. Visual observations of the samples indicated that the darkest dye color was noted at 30 feet and 20 feet. Medium color (as compared to the darkest samples) was noted at 40 feet and 1 foot. Samples collected at 10 feet were the lightest indicating that the surface color noted was likely due to drag up of dye from the effervescence noted during slack tide conditions and that the bulk of the supersaturated water was dispersed in the mid-depth of the water column that corresponded to the return line outlet depth.

Observations were made to determine if the dye was noticeable upstream of the ReOx System. Observations made showed that the only visual evidence was from the surface release. There was little evidence at the GPA Berth 20 Dock of the dye. This confirmed the hypothesis that the superoxygenated water remained largely within the navigation channel.

4.8 OTHER MONITORING AND ANALYSES

4.8.1 USGS Gage at USACE Dock

Provisional water quality data from the USGS Gage 021989773 Savannah River at USACE Dock, at Savannah, GA matched very closely the data from deep monitoring zone USACE monitoring station data collected by MACTEC, Appendix B Geodatabase, referenced as Table USGS_Gage_Data. The USGS station was set at approximately 4 feet from the bottom at the USACE dock. Figure 4-8.1 presents the USGS provisional water quality data at the USACE dock (USGS, 2007a).

4.8.2 USACE Kings Island Turning Basin Monitoring

The USACE provided water quality data taken at various locations in the Savannah River while dredging was occurring upstream from the ReOx barge location. These data are shown in Appendix C.

4.8.3 USGS Gage at Clyo

The USGS gage station data from the Savannah River near Clyo, GA, USGS 02198500, for July 9, 2007 through September 25, 2007, are provided in Appendix A, Geodatabase, referenced as Table USGS at Clyo and are provisional. Figure 4-8.2 depicts streamflow data for the Clyo gage. The data showed an average flow rate of 5086 cubic feet per second (cfs) during the ReOx project (USGS, 2007b). The maximum flow, 5650 cfs, on 7/14/2007 and the minimum flow, 4590 cfs, on 7/25/2007 at the Clyo gauge were both prior to the ReOx system startup. During the monitoring period of July 9 through September 25, 2007, instream flow was observed at and sometimes below critical instream flow conditions of 5000 cfs.

4.8.4 Rainfall Monitoring

The rainfall data have been included on Figures 4-2 of the stationary monitoring locations. These data are provided in Appendix A Geodatabase as provisional from the USGS Gage 021989773 Savannah River at USACE Dock, at Savannah, GA weather station, referenced as Table USGS_Gage_Data. The maximum rain event between July and September 2007 was on 7/30/2007 with 12.59 centimeters (approximately 5 inches) of precipitation. The maximum weekly rain event occurred between July 30th to August 5th with a total weekly precipitation of 18.84 centimeters (7.4 inches) (USGS, 2007a).

4.8.5 Data Analysis by Georgia Tech Students

- Data provided by GPA to Civil and Environmental Engineering students at Georgia Tech.
- Reviewed/analyzed only data from continuous near-bank monitoring locations. and did not analyze more-representative centerline or cross section monitoring.
- Compared DO percent saturation before, after, and during project for all tides combined such that progressive sea cooling effect on high tide data masked low-tide deficit reductions
- Concluded there was not a statistically strong positive impact on DO as a result of oxygen addition.
- While MACTEC appreciates the contribution of the Georgia Tech students, it is important to note that their conclusions are based entirely on the near-bank monitoring while the dominant influence of the ReOx project was on the central part of the river (USACE, 2007).

5.0 FULL-SCALE DESIGN CONSIDERATIONS

Locations for permanent stations will require certain infrastructure to support the operations of the ReOx systems. For example, a station incorporating liquid oxygen will require a road so that the tanker trucks delivering the liquid oxygen would be able to have access to the site. A station incorporating an oxygen generator would be able to utilize a more rudimentary road for access for the personnel who will be servicing and operating the system. Electrical service will be needed to supply power for the pump system.

The ReOx discharge lines should be placed as deep in the river as possible and preferably discharge toward the navigation channel or river bottom. For example, the design of the demonstration project included discharge lines that sloped downward approximately 10 degrees (from horizontal), and the momentum of the water flow transported the supersaturated water into the navigation channel. A similar approach should be considered for the permanent installation to simplify the discharge pipe layout. Discharge lines should be placed so they present the least possible impact on normal river operations (ship traffic, dredging, etc.) and may be seasonally deployed.

5.1 CONCEPTUAL DESIGN SCHEMATICS

Based on the results of the demonstration project, MACTEC anticipates that two permanent installations would be sufficient to provide oxygen to mitigate the effects of harbor deepening, with one station having one cone (but designed with the contingency of adding a second cone) and the other station having two cones (an extra to allow one cone to be down for maintenance at either station). Additionally, each system should have a backup pump system so that operation could continue during pump maintenance or failure.

Depending on the sites selected for permanent installation of ReOx stations, there are several possible design scenarios to consider, including:

- River bank below ground installation of the Speece Cone (Figure 5-1)
- Above ground installation of the Speece Cone (Figure 5-2)
- Barge mounted systems similar to the demonstration project

Each of these alternatives, depending on site location and access, could take advantage of various design alternatives such as: a single or dual cone design; intake screen type; and oxygen generation or liquid oxygen supply. Figures 5-1 and 5-2 provide a general conceptual layout of two types of mounting configurations for single cone systems that may be adapted to dual cones systems as needed. Final design layouts for a permanent system will depend on site-specific requirements.

5.2 ESTIMATED COSTS TO CONSTRUCT

As a planning tool, MACTEC has prepared rough order of magnitude (ROM) estimated costs for one cone stations based on the conceptual designs presented in Figures 5-1 and 5-2. Table 1 presents the ROM estimated costs for a basic one-cone land-based ReOx Station. These costs do not include land procurement, utility installation, or roadway construction as these are highly dependent on the actual sites selected. Costs presented in Table 5-1 are summarized below:

- Above Ground Installation – Oxygen Generator: $1.90 million
- Above Ground Installation – Liquid Oxygen Supply: $2.05 million

- Below Ground Installation – Oxygen Generator: $4.80 million
- Below Ground Installation – Liquid Oxygen Supply: $4.95 million

Additional considerations for the design of each permanent ReOx station location would be the annual O&M requirements. Estimated ROM annual O&M costs per cone are presented in Table 5-2 and are summarized below.

- Oxygen Generator: $24,000
- Liquid Oxygen Supply: $131,000

Additional costs would include the cost of a support building at each ReOx Station. The support building would house equipment, control panels, oxygen generation equipment (if applicable), and provide off-season storage of ReOx pumps, Speece Cone(s), and other equipment. Building costs will vary depending on the type (prefabricated, block, or concrete) and the finish required (some areas may have specific design requirements, i.e. brick, rock, etc.) for a specific location selected. These costs range from $150,000 to $300,000 or more. The below ground installation is more expensive because sheet piling and dewatering would be required during installation.

6.0 ANECDOTAL INFORMATION

- The Nature Conservancy conducted sturgeon monitoring in the vicinity of the ReOx project using underwater receivers to monitor whether tagged fish pass by a particular Savannah River section. No tagged sturgeons were noted during the ReOx demonstration project.

- It was necessary to scrape off barnacles from the continuous monitoring sondes routinely as part of the operation and maintenance procedures.

- When the ReOx system return lines were disassembled and brought to the surface, blue crabs were noticed on the return lines which they were using as habitat structure.

- The mid-channel and cross section transect data were collected from a registered boat and carefully coordinated with the United States Coast Guard and other pilots navigating the Savannah River.

- The ReOx demonstration project used four 400 horsepower pumps that were mounted on the barge deck. The rated decibel levels were 72-76 decibels for each pump at 30 feet. It is expected that the vertical pumps planned for the permanent installations would generate approximately 65 decibels for each pump at the pumps on the barge deck.

7.0 CONCLUSIONS

1. **The ReOx system was able to meet the target oxygen mitigation quantity of 20,000 ppd.** The goal of adding enough oxygen, approximately 20,000 ppd, to mitigate the effects of harbor deepening was achieved using two Speece Cones each designed for up to 15,000 ppd.

2. **Operation of the ReOx system resulted in an average decrease of the DO deficit of 0.6 mg/L.** Mid channel DO profiling along the river study length indicated that about three days of continuous oxygen injection were needed to initiate measurable DO deficit reduction and that an overall average deficit reduction of approximately 0.6 mg/L was achieved during the demonstration period as compared to pre- and post- monitoring data.

3. **The positive effects on water quality from the ReOx system were notable after system shutdown**. For at least seven days after the ReOx system was shut down, residual positive effects of oxygen addition were still clearly evident in nearby cross-section transects taken at low tide. Ten days after ReOx system shut down there was no continuing evidence of residual instream DO improvement, and mid-channel low tide DO deficits had substantially returned to pre start-up deficit levels of 3.9 mg/L.

4. **Near barge monitoring did not detect excessively high DO concentrations in the river.** Immediately after startup, the near barge monitoring performed around the ReOx system at the request of EPD indicated that the superoxygenated river water was dispersing quickly into the tidal flow of the Savannah River system. Continuous stationary and periodic mid-channel and cross section monitoring also indicated that the superoxygenated river water was dispersing quickly into the river system.

5. **Influent monitoring concluded no short circuiting of the reoxygenated water.** The influent water pumped into the system from the river was not oxygen rich; thus, tidal movement effectively transported new water into the target injection area.

6. **Data collected by project monitoring activities was verified by USGS monitoring.** USGS water quality gaging station data closely matched MACTEC water quality deep monitoring data at the USACE dock.

8.0 REFERENCES

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