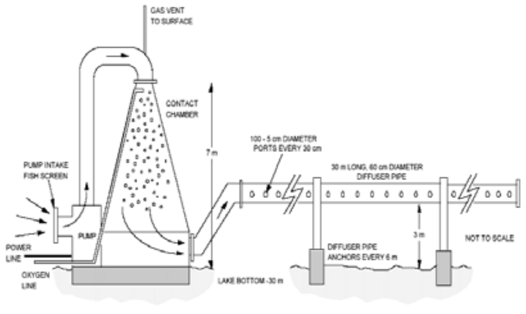


Figure 2 - Schematic of submerged contact chamber oxygenation system used in Camanche Reservoir, California and Newman Lake, Washington.

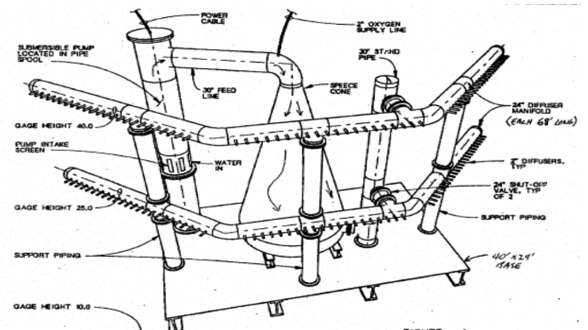


FIGURE - 1

STANDLEY LAKE - SPEECE CONE SYSTEM
ISOMETRIC

B. U-Tube Pilot Study

Deep U-Tubes offer excellent potential as energy and cost efficient oxygen transfer systems. The depths of 25 to 60 m appear to be most useful for optimal oxygen absorption.

U-Tubes have been used for aeration of:

- fish hatchery water
- sewer mains
- free-flowing rivers
- activated sludge treatment

Mixed liquor oxygen transfer energy has proved to be comparable or superior to that produced by conventional surface aerators, and produces dissolved oxygen concentrations in the discharge which exceed saturation under ambient conditions. Even D.O. levels in excess of 200% can be produced with an oxygen transfer energy efficiency of 4 kg of oxygen per kwhr.

The ICI deep shaft process is operational at a number of waste water treatment locations in Europe and Canada but there is only operational information available for one depth and velocity at each location. Design criteria were not yet available to estimate rationally sizing costs and to predict the operational characteristics of deep U-Tubes for any of the above potential applications.

In order to include U-tube aeration as an alternative design the design engineer needs to ascertain the following data:

- depth required
- throughput velocity
- appropriate gas/water injection rate
- discharge D.O. target
- head loss across U-tube to determine energy consumption.
- oxygen transfer economy and kilograms of O_2 per kwhr
- oxygen cost per ton, which includes the amortized capital plus the electricity to operate the system.

The pressure loss across a U-Tube system due to oxygen injection is shown in Figure _____ as a crosshatched bar. The pressure loss across the 1/10 meter diameter U-Tube due to frictional losses alone is shown as the open bar on top of the crosshatched bar. The calculated frictional loss of a 1 m^2 U-Tube is noted on the graph by the solid bar since this larger pipe size would be the best prototype system.

The oxygen transfer per kwhr is calculated for a prototype U-Tube with 1 m^2 of cross-section in both the up and down legs. This energy consumption data is shown in

Figure ___. It is seen that a U-tube depth of 30 m and 25% O2/water injection ratio yields 12 kg of oxygen per kwhr as the energy consumption ratio. It should be noted that recycle of the gas would change the oxygen composition from 100% to approximately 70%, due to stripping of dissolved nitrogen from the influent water. This would tend to reduce the kilograms of oxygen per kwhr accordingly. There is essentially little practical incentive to attempt to improve oxygen transfer energy consumption beyond 200 kwhr/ton D. O. because such savings in energy per metric ton of oxygen dissolved are negligible. Therefore the high rate of oxygen transfer at 30 m depth and 4% O2/water ratio, which is 25 kg of O2 per kwhr, is not worth exploiting.

Pilot Study Evaluation Criteria

The following parameters were evaluated:

- velocity: 0.9, 1.4, and 1.8 m per second.
- depth: 12, 30, 61 and 103 m deep.
- oxygen injection ratio: 7.5% to 25% oxygen/water ratio.

U-Tube Pilot Study Preparations

A pilot U-tube facility was constructed with 0.1 meter diameter pipe in a 0.3 m diameter hole that was 120 m deep. The U-tube depth was adjusted as desired to evaluate the following parameters:

- depth at 12, 30, 60 and 103 m respectively
- velocity at 0 .9, 1.4 and 1.8 m per second respectively
- injected air and pure oxygen
- pure oxygen gas injection ratio 7 1/2 and 25%
- tap water and simulated wastewater with 5 mg/L of anionic detergent and 100 mg/L bentonite.

The experimental data were collected for each set of conditions according to the inlet D.O., discharge DO, pressure loss across the U-Tube and water temperature. Due to the fact that D.O. concentrations in excess of 100 mg/L were encountered, special procedures were developed to ensure accurate D.O. measurements at these unusually high concentrations.

Throughput velocity was based on the nominal velocity of the water alone without gas injection. Thus the actual velocity in the gas/water mixture would vary somewhat throughout the U-Tube because of the hydrostatic compression of the gas phase. Nominal velocities of 0.9, 1.4 and 1.8 m per second were investigated and are shown in Fig. ___ . There is a practical lower limit of nominal velocity below which the U-tube will not function in a stable manner.

It is noted from Fig. _______ that there is no consistent effect of nominal velocity on the increase in D.O. across the system. In some cases nominal velocity (1.4 m per second) gave slightly higher or lower increase in dissolved oxygen. Lower velocity increased the bubble contact time within the U-Tube as well as lowered the Reynolds number, but apparently these two effects nullified each other.

The pressure at the inlet and discharge was recorded for each set of experimental conditions. The pressure loss across the system was composed of losses due to hydraulic friction, bubble drag and differential void volume in the down and up legs. Hydraulic frictional losses are a function of the pipe diameter. The bubble drag and differential void volumes in the two legs were observed to be independent of pipe diameter.

For each set of experimental conditions pressure readings were taken before any gas was injected into the U-Tube and after the desired gas water injection ratio was established. In this manner, the two components of pressure loss across the U-Tube could be identified.

Oxygen absorption efficiency can be achieved by either of two approaches when using U-Tube technology. The O2/water ratio and the U-tube depth and velocity can be matched to result in 90% oxygen absorption efficiency in one pass through the U-tube. Or with a second approach a high O2/water ratio may be injected into a more shallow depth U-Tube shaft but must provide for capture of the bubbles in the discharge to re-inject these fugitive bubbles back into the inlet.

Low, intermediate and high O2/water ratios were investigated, namely 4, 7.5 and 25%. These results are shown in Figure 13. The dotted line in Figure 13 indicates the 90% oxygen absorption range. It can be noted from this graph that even at 103 m depth less than 90% oxygen absorption occurs with 1% O2/water ratio resulting in a change in D.O. of only 9 mg/L. In this case the increase in D.O. level and U-tube depth are impractical. Consequently the second approach is the best alternative, namely high O2/water injection ratios incorporating gas capture and recycle.

The study revealed that the optimum design of a U-tube oxygenation system operating at minimal cost incorporates a depth of 25 to 60 m, a velocity of 1.8 to 3.0 m per second, and an O2/water injection ratio of 25%.

This portion of the pilot study revealed that a substantial increase in dissolved oxygen resulted at 61 m depth in comparison to 30 m depth. However at 103 m there was little increase in D.O. across the system in comparison to the 61 m depth (see Fig. __).

Results

Fig. __ indicates that only minor variations in change in dissolved oxygen were observed over the velocity range tested. This is fortunate because the maximum nominal velocity was thus limited only by frictional head loss considerations, and therefore permitted very high tonnage of oxygen dissolved per cubic meter of U-tube. Such a high rate of dissolved oxygen offsets to a large degree the capital expenditure for the deep shaft hole.

It was not possible to achieve 90% oxygen absorption in a 103 m deep U-tube even though the injection gas ratio was less than 1%. At such low gas water ratios there would not be any effervescent loss of dissolved gas. Even lower oxygen absorption efficiencies would be observed in water containing surfactants. This observation contradicts the claim of Hemming *et al*, that all of the gas phase is dissolved in deep U-Tubes, and that some subsequently comes back out of solution in the upper region of the up leg.

Very encouraging results were noted with a particular O2/water ratio combined with the 61 m depth shaft: 96 mg/L D.O. concentrations were found in the discharge using a 25 % O2/water ratio. The estimated unit energy transfer and total costs amounted to 12 kg of D.O. per kwhr and $6.50 per ton of D.O. added. But there was little advantage found in operating as U-Tube in excess of 61 m depth.

According to the pilot study when pure oxygen was injected at 25% O2/water ratio at 30 m depth, the dissolved oxygen increased from 68 mg/L to 95 mg/L at 61 m U-Tube depth. Negligible improvement in dissolved oxygen concentrations were observed after 103 m depth.

Over the velocity range investigated of 0.9 to 1.8 m per second, there was no significant effect on increase in D.O. The maximum absorption efficiency for pure oxygen at 7.5 % O2/water injection ratio was observed to be 52% in the 103 m deep U-tube, demonstrating that the U-tube requires capture and recycle of the off gases if it is to be used in an efficient manner as the absorption system for an oxygen supplementation station.

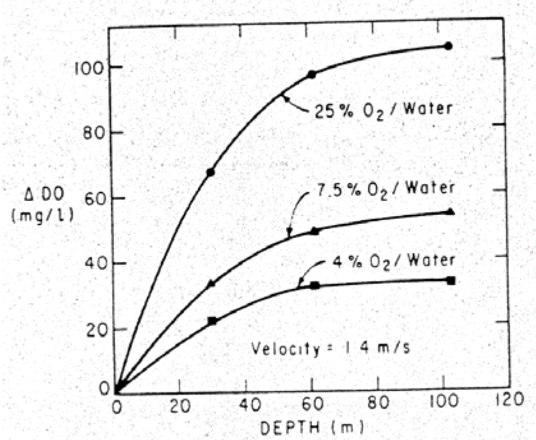


Fig. 11. Δ DO vs Depth for Oxygen Injection

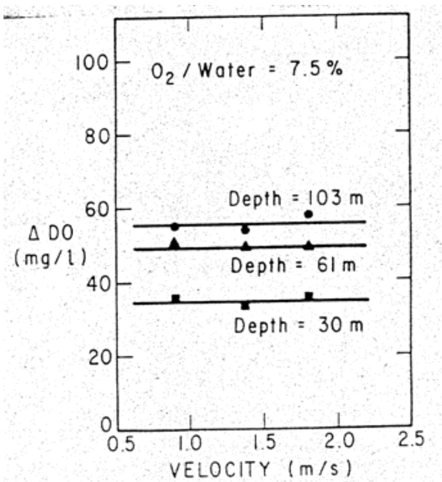


Fig. 12. Effect of Velocity on Δ DO for Oxygen Injection

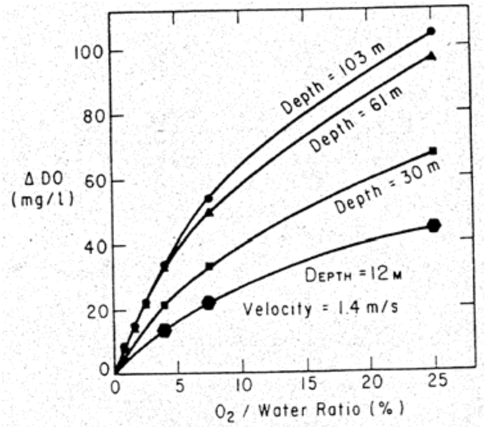


Fig. 13. Effect of O_2 / Water Ratio on Δ DO

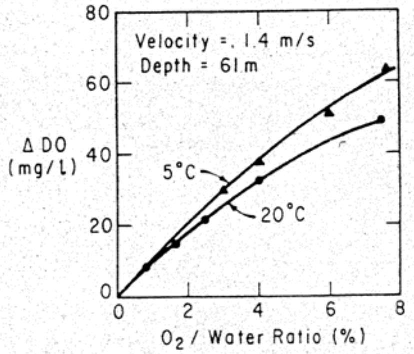


Fig. 14. Effect of Temperature on Δ DO for Oxygen Injection

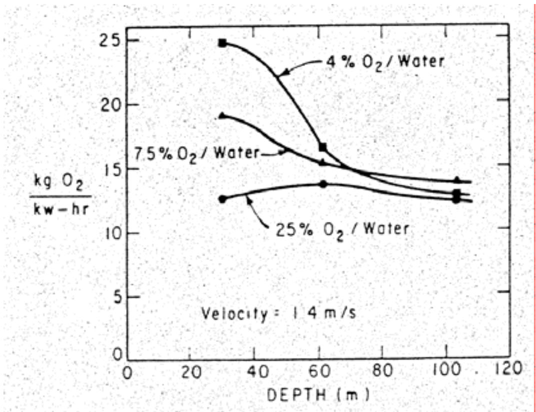


Fig 18 Oxygen Transfer Energy vs Depth – O_2

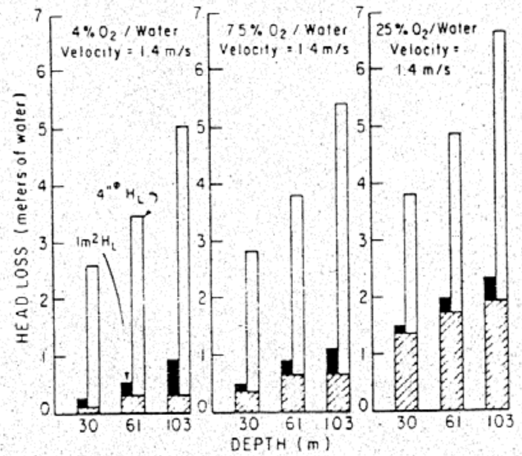


Fig 17 Headloss Breakdown into Frictional Losses and Loss Due to Oxygen Injection

An Existing U-Tube Application on the Tombigbee River, Alabama

U-Tube Oxygenation was selected for the two oxygen supplementation locations on the Tombigbee River. The U-Tube with oxygen injection produced an effluent D.O. 50 mg/L at 28° C. within oxygen absorption efficiency of 80 to 90% for a unit energy consumption of 94 kWh per ton of D.O.. The oxygenation capacity was 5400 mg/L of D.O. per U-Tube volume per hour, and the head loss across the 175 foot deep U-Tube was 5 feet. A bubble harvester is desirable to harvest any undissolved bubbles and recycle them back to the influent of the U-Tube. By discharging a highly elevated D.O. sidestream into the river through a diffuser in the bottom, advantage was taken of the hydrostatic head to prevent effervescent loss of D.O. and a high D.O. discharge was mixed throughout the river cross-section within a short distance downstream.

A schematic diagram is shown of both the gravity fed to U-Tube which puts in 12,000 pounds of D. O. per day, as well as a schematic of the U-Tube where 125 MGD of water is pumped from the river through the U-Tube and then discharged back into the river with 50 mg/L of supersaturated D. O. concentration, resulting in 40,000 lb/day supplementation.

Field testing at James River of the U-Tube, which oxygenated the treated effluent from a James River mill, yielded the following observational operational results:

- discharge D. O. of up to 50 mg/L at 25°C in the water
- head differential across the U-Tube was 5.3 ft and
- oxygen transfer capacity of up to 18,000 pounds of D. O. per day and
- oxygen absorption efficiencies of 80 to 90% were realized.

Advantages of the U-Tube Technology

Table V. The major advantages of U-Tube oxygenation, which led to its selection for remediating the Tombigbee River D.O. depletion problems, were as follows:

1. efficient oxygen absorption of 75 to 90%
2. high rate of oxygen transfer per unit volume of reactor, up to 5400 mg/L per hour, versus 100 mg/L per hour for conventional aeration tanks and
3. unit energy consumption per ton of D. O. add was approximately 100 kWh per ton of D. O., which is low because head loss across the system is low even though oxygen transfer occurs at hydrostatic pressures up to 175 feet
4. high D. O. concentrations of up to 50 mg/L at 28°C
5. exceptionally high D. O. saturation concentrations generated enabling supersaturation of D. O. in its discharge.
6. oxygen bubble contact time prolonged
7. pressurization of the oxygen gas bubbles provided by hydrostatic pressurization
8. negligible energy consumed in contrast to the excessive energy consumption of pumped pressurized vessels which lose all of the input energy across the pressure throttling valve (thus also potentially losing supersaturated D. O. concentrations by effervescence)

9. no external pumping required if the water being discharged was at 30 foot above river level
10. stripping of dissolved nitrogen gas from the water minimized
    with consequent nitrogen gas dilution of the oxygen composition of the bubbles because gas transfer is occurring in a pressurized vessel (water saturated with nitrogen in air will strip if the nitrogen partial pressure in the gas phase is less than 0.79 atm.) If the process is at atmospheric pressure the nitrogen compensation approaches a theoretical value of 79%, but at four atmospheres the nitrogen composition approaches a theoretical value of only 20%.

Section 5. Mixing and Transport in Harbors

5. Mixing and Transport of D.O. within Savannah Harbor

I. Requirements for Meeting D.O. Standards for Savannah Harbor

A. Essential Requirements for Harbor Mixing and Transport

The following essential components must be successfully incorporated into an oxygenation system to meet D.O. standards throughout Savannah Harbor:

- dissolving requisite D.O. (lb D.O./day)
- transporting D.O. evenly throughout the harbor
- strategically locating oxygen supplementation stations so that tides, propellers or horizontal flow diffusers can transport superoxygenated discharges effectively
- utilizing large diameter propeller pumps or horizontal flow diffusers to transport the oxygen away from the location where it superoxygenated water is generated

B. Diffuser Design Considerations

Once the sidestream is highly oxygenated it must be reintroduced into the hypolimnion and transported throughout the entire impoundment. Such success requires special considerations in the diffuser design as follows:

- jet velocity in diffuser ports
- number of diffuser ports required
- spacing of diffuser ports
- height of diffuser above sediments
- direction of diffuser ports
- velocity of horizontal jet less than the re-suspension velocity of the sediments when reaching the bottom of the impoundment
- velocity of horizontal jet sufficiently low enough to prevent erosion of the underside of the thermocline when reaching the top of the hypolimnion

C. Horizontal Flow Design Possibilities

Velocity of horizontal jets must be sufficiently low to prevent erosion of the overlying fresh water. Such design considerations are especially critical in shallower impoundments such as Savannah Harbor. In one installation where Prof. Lawrence of the University of British Columbia provided the design of the diffuser, the impoundment was less than 30 feet deep, and the hypolimnion was only about 15 feet deep. After one season of operation, stratification was maintained, bottom sediments were not resuspended and D.O. was transported to regions of the hypolimnion that were approximately two miles away from the oxygenator diffuser.

A key consideration in supplementatal oxygenation of Savannah Harbor is to induce a superoxygenated sidestream to flow horizontally across the bottom layer ofmore dense water where D.O. is more needed than in the upper surface of the water column.

At Camanche Reservoir a diffuser was located at the toe of the dam. It dissolves 18,000 lbs of oxygen per day in a sidestream of 35 ft3/sec withdrawn from the hypolimnion and discharged through a 100 ft long diffuser. It is located near the dam in the vicinity of the bottom penstock. When the water is 100 ft deep, the sidestream that is oxygenated has a D.O. of about 100 mg/l. The diffuser discharges toward the head end of the reservoir and a D .O. increase of 4 mg/l was observed in the hypolimnion 10,000 feet from the diffuser about two weeks after operation commenced. Oxygen supplementation of the hypolimnion allowed power to be generated, prevented hydrogen sulfide production, and met the D.O. criteria for the river and fish hatchery. This system is hidden from public view at the bottom of the reservoir, another strong recommendation.

II. Spacing of Oxygenation Stations for Maximum Mixing and Transport within the Harbor

A. Limitations on Zones of D.O. Supplementation Influence

There is an economy of scale associated with oxygen supplementation stations which favors the utilization of fewer and larger stations. This likewise is reflected in greater distances between oxygenation stations. Since a key consideration in any supplemental oxygenation system is that the superoxygenated water must be transferred away from the location where it is being superoxygenated, this places certain limitations on the spacing of the supplemental oxygenation systems. Transport of the superoxygenated water away from the superoxygenation station can be accomplished by:

- tidal action
- discharge jets
- large diameter slow-moving propellers

Thus, there are certain limitations on the zone of influence for oxygen supplementation from a given fixed location. If there is negligible tidal action and if there is not the availability of large diameter, slow-moving propeller pumps to move the water away from the fixed location, then there will be a limitation on the distance between supplemental oxygenation stations. Also there may be certain regions within the harbor that have very little tidal action mixing or are shielded by peninsulas of land or other such obstructions which prevent the movement of superoxygenated water into that area.

Such isolated zones will require special attention to theincorporation of large diameter propellers or location of oxygenation stations in that particular zone. This may be accomplished by mobile systems as described below.

B. Effective Circulation of Oxygenated Discharges Throughout the Harbor

In addition to the mixing/transport accomplished by tidal action, it may be necessary to incorporate additional mixing/transport mechanisms to move the superoxygenated water away from the location of the oxygenation station. Unless the superoxygenated water is moved away, eventually a ‘hot spot’ of highly oxygenated water will short circuit back through the oxygenation station reducing the efficiency of O2 absorption.

There are various means which can insure that the requisite transport/mixing is accomplished. The large diameter slow moving propellers are very efficient in moving large quantities of water with little energy required. Following are pictures of two types of these devices. In both cases, a screen enclosure is required to preclude harm to swimmers. The results of hydrodynamic modeling of the plumes indicates that the momentum imparted by the propellers can move the water over two miles away from the source. The graphs of such models are shown below.

Properly designed diffusers can also insure that the oxygenated water moves out of the zone where it was produced. Following is also a schematic view of a diffuser designed to insure that the oxygenated water is added at various depths throughout the water column if needed. If it is desirable to place the superoxygenated water in the bottom layer, then only the lowest diffuser would be employed.

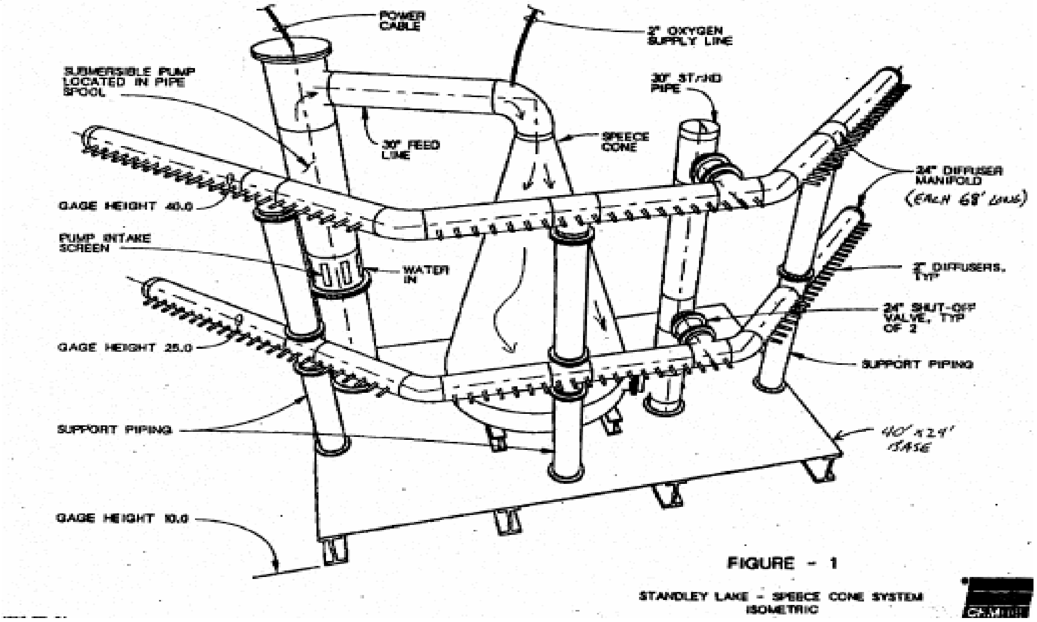


FIGURE - 1

STANDLEY LAKE - SPEECE CONE SYSTEM
ISOMETRIC

Figure 1. Cross-reservoir velocity profiles

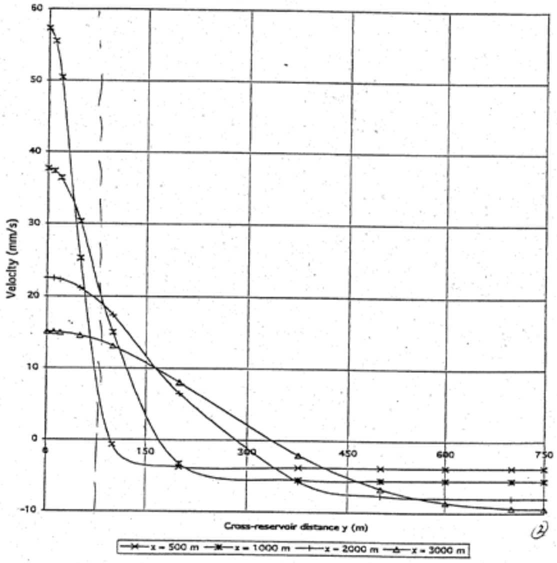
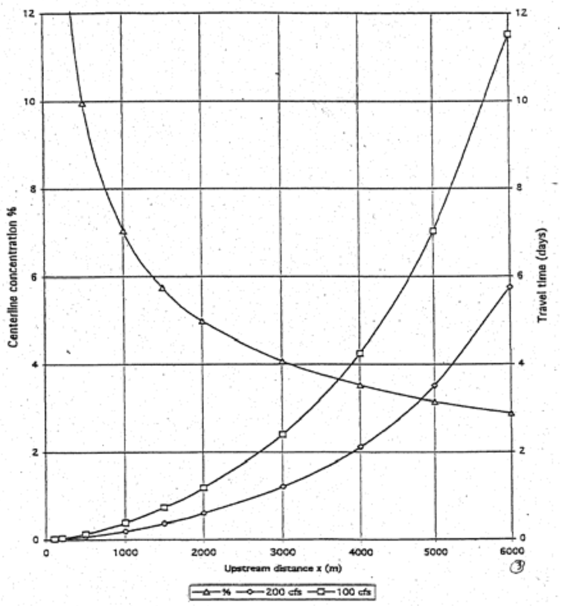
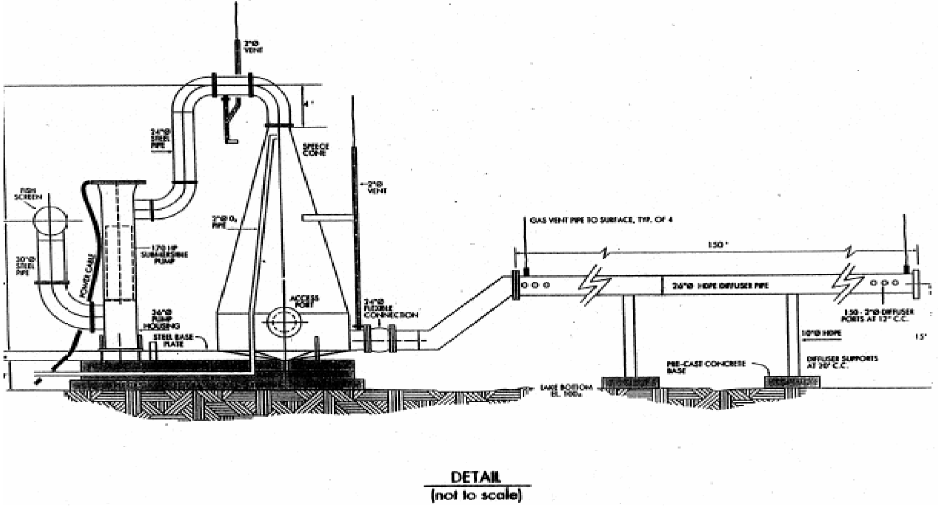
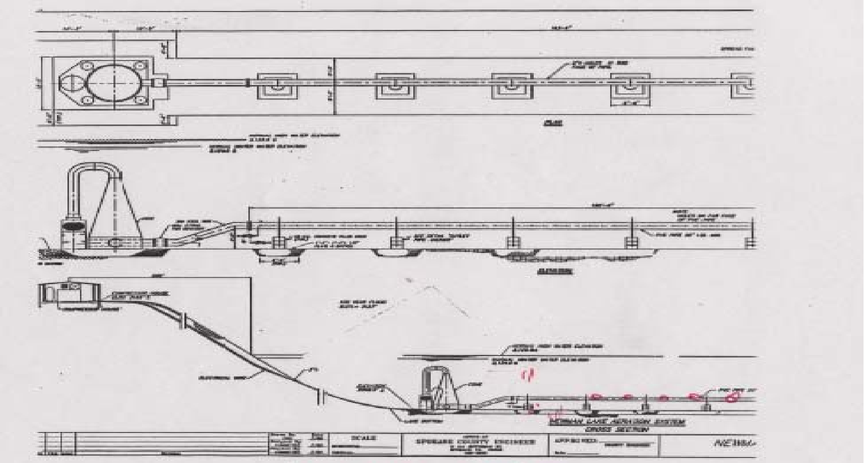


Figure 2. Travel times and dilutions



CAMANCHE HYPOLIMNETIC OXYGENATION DEMONSTRATION PROJECT
SPEECE CONE AND DIFFUSER PIPE DETAIL





HYPOLIMNION - 21 FT DEEP

CIRCULATE 1 TO 2 MILES AWAY

III. Mobile Barge Oxygenation Advances

A. Advantages of Self-Contained Mobile Oxygenation Barges

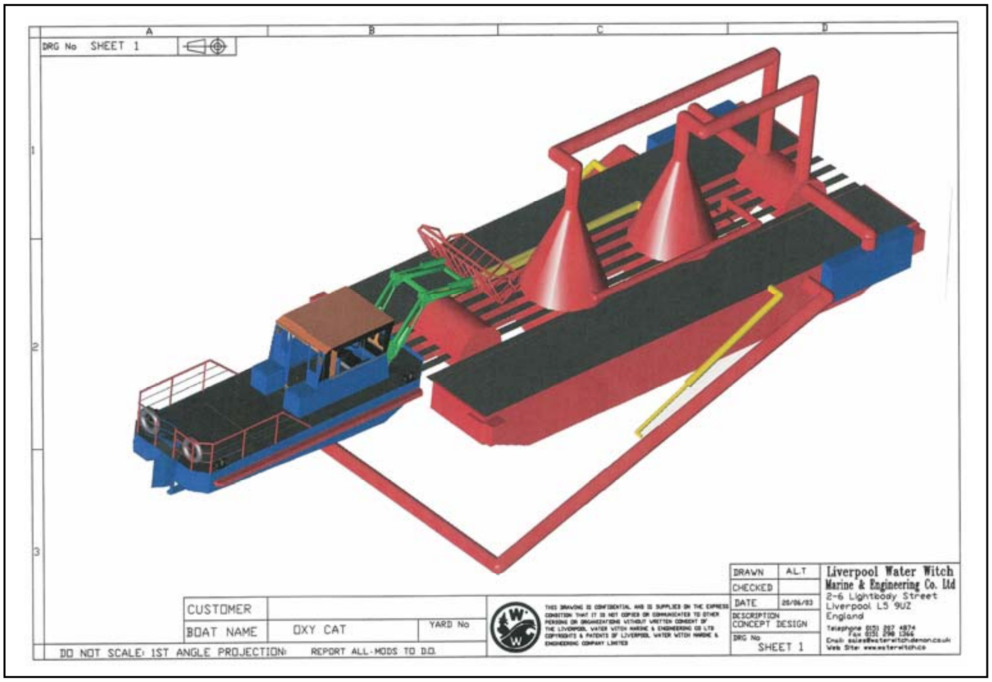
A key consideration in supplementing oxygen to the harbor will be the availability of land at key locations dictated by D.O. deficiency conditions within the harbor, upon which the oxygenation system could be placed. The availability of electricity is another consideration. Generally it is quite expensive to bring in electricity and the demand charge component of the cost can considerable. So these two facets, the availability of the real estate in the vicinity of the place where the oxygen is needed and the availability of electricity brought to that location will be significant economic factors.

Mobile oxygenation barge systems such as are used in the Thames River, Shanghai Harbor and Cardiff Bay would be a practical choice for use in Savannah Harbor since a barge mounted unit would supplement the oxygen directly into the harbor. Such barge units hold a unique advantage in that they can either be tied up permanently at a given location or moved to various oxygen depleted locations within the harbor, without requiring land use.

This type of unit can be self-contained with its own PSA oxygen generation source, which could be driven by an internal combustion engine that requires no electrical power being brought in. The pumps required to move water through the oxygen transfer vessel can also be powered by combustion engine driven pumps. Another alternative is to utilize an engine driven electrical generator to power the PSA generation system as well as the pumps supplying the oxygen absorption reactors. Thus the barge units would only need to be supplied with diesel fuel. In some cases, propane driven pumps have been used to anticipate the possibility of a spill in the harbor. Propane with its volatile nature would not present a pollution problem if spilled into the harbor such as diesel fuel would.

Thus in the overall strategy for meeting the dissolved oxygen standard for Savannah Harbor, it may be appropriate to consider the provision of one or more mobile oxygenation units which are self contained except for the need of periodic fuel delivery. These mobile oxygenation units would be moved to areas which were not readily impacted by fixed location supplemental oxygenation stations.

The mobile oxygenation system would operate with the oxygen absorption reactors lowered to the bottom of the harbor to take advantage of the hydrostatic head enhancement of oxygen transfer and would be raised during transport. Schematics of a proposed mobile oxygenation station are shown below.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DRAWN A.L.T
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Liverpool Water Witch Marine & Engineering Co. Ltd
2-6 Lightbody Street
Liverpool L5 9UZ
England
Telephone 0151 207 4874
Fax 0151 298 1366
Email: sales@waterwitch.demon.co.uk
Web Site: www.waterwitch.co
CUSTOMER
BOAT NAME OXY CAT
YARD No
DO NOT SCALE: 1ST ANGLE PROJECTION: REPORT ALL-MODS TO D.O.
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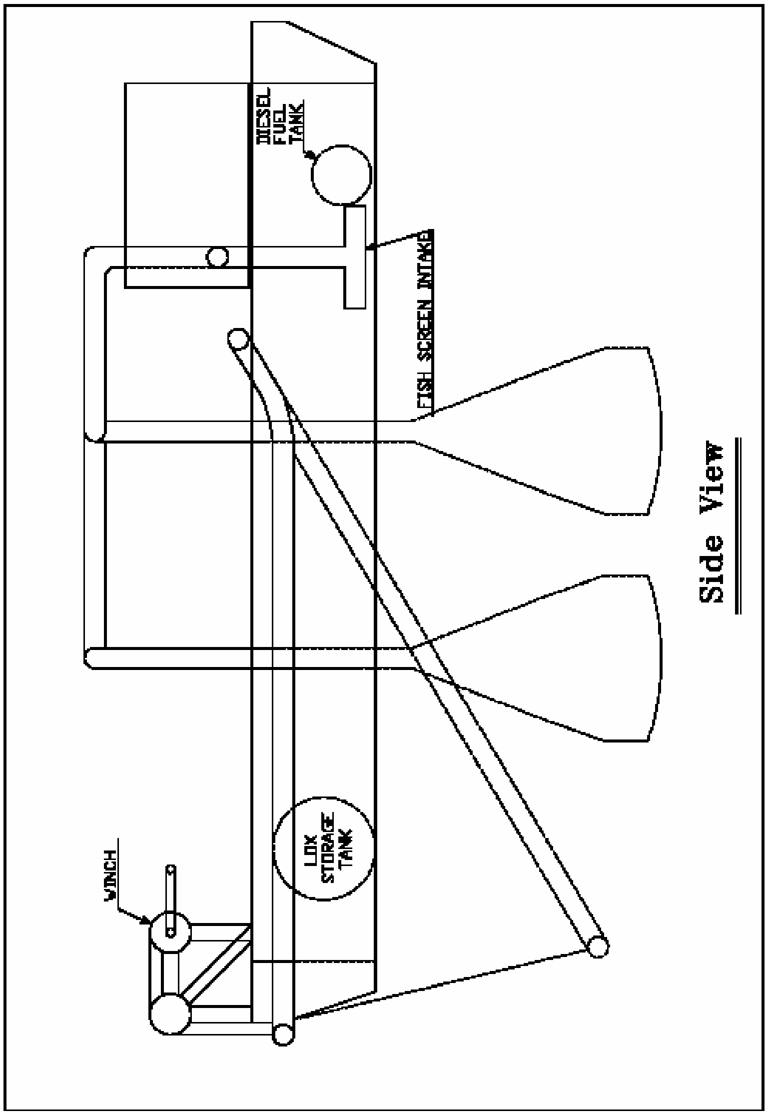
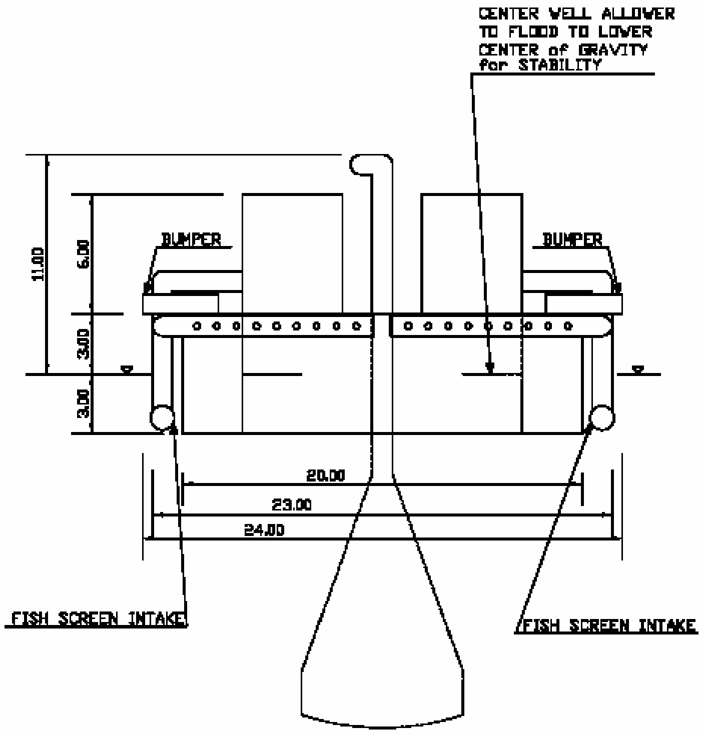


Side View


CENTER WELL ALLOWER
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FISH SCREEN INTAKE
FISH SCREEN INTAKE

End View

B. Thames River Oxygenation Barges

One large world class ship channel area which employs a mobile oxygenation system is the busy Thames River in London with its “Thames Bubbler and “Thames Vitalizer” self-contained barges.

Historically the Thames River has had occasional oxygen deficiencies. These dissolved oxygen deficiencies have been related to combined sewer overflows resulting from storm events. They are further exacerbated by residual organic loads in the treated effluents being discharged into the river. In an attempt to comply with the dissolved oxygen standard in the Thames River, a mobile oxygenation system that has been dubbed the “Thames Bubbler” was constructed. This system is a motorized barge that contains a 40 ton per day, PSA oxygen generation unit. Thus the oxygen is generated on site and the oxygen transfer system incorporates a series of Venturi jets extending from the barge unit itself. Whenever a section of the Thames River has dissolved oxygen concentrations below the targeted standard, the mobile oxygenation unit is transported to that stretch of the river, where it supplements the oxygen until it meets the targeted D.O. Water is withdrawn from the river and pumped at high pressure and velocity through the venturi jets which aspirate high purity oxygen into the throat of the venturi. The same performance characteristics would apply to these venturi oxygen transfer units, as are described above for evaluation:

- the unit energy consumption per ton of dissolved oxygen
- the relative oxygen absorption efficiency
- the level of super oxygenation, which can be achieved in the discharge

C. Example of Bay Mobile Oxygenation: Cardiff Bay, England

A dam has been constructed across the mouth of Cardiff Bay in England to segregate tidal action from the Bay, thereby eliminating the exposed mud flats at low tide within the Bay which cause malodorous conditions during low tide. In order to comply with D. O. standards within the estuary inside the impounded area, a series of air diffusers was placed on the bottom of the bay. Air was injected into these diffusers in order to mix the water column, as well as provide some oxygen transfer.

Because D.O. deficient conditions occur within the impoundment in the bottom waters in some areas, it was decided to provide a mobile oxygenation system unit, which could be transported to those areas and inject super oxygenated water into the prescribed vertical elevation a wedge of water. An oxygen transfer device was constructed and placed upon a barge, which is moved to any area within the Bay to satisfy the D.O. deficit in a particular layer of water in any region of the bay.

IV. Horizontal Placement of Superoxygenated Discharge in the Water Column

A. Advantages of Horizontal Placement of Superoxygenated Side Stream

Because the anaerobic sediment /water interface is the key location for bottom dwelling organisms and adverse water quality transformations, it follows that any remedial D.O. supplementation scheme should focus on maintaining this interface as oxic as possible to prevent the above mentioned water quality degradation

Superoxygenation of the harbor sediment interface using properly designed equipment is reported to be more beneficial than simply oxygenating the water column near the surface. Such an oxygenation alternative has emerged only recently. This important type of superoxygenation system successfully incorporates the following features:

- the salinity stratification is maintained intact and in place
- highly efficient oxygen absorption must be attained
- oxygen transfer turbulence is contained within the oxygen transfer reactor and is thus minimized to p
- revent destratification
- effective placement is achieved
- benign environmental impact is sustained

The relatively high concentration of microorganisms at the sediment/water interface, compared to their concentration in the water column, results in this zone dominating water quality transformations such as iron and manganese reduction and hydrogen sulfide production.

B. Difficulties of Free Rise Bubble Plume Systems in Sediment Oxygenation of the Water Column

A classic mode of D.O. supplementation is to inject air or oxygen into a diffuser located near the bottom. The buoyant nature of the bubble causes it to rise vertically and thus to impart a vertical movement of the water in the vicinity of the bubbles column. Eventually near the thermocline, the rising bubbles uncouple from the rising water column when the circulation pattern is weak and unable to overcome the water density differential.

If the vertical rise velocity of the water entrained in the bubble plume is sufficiently high, both the bubbles and water rise all the way to the water surface, at which point the water velocity turns horizontally and eventually downward to replace the water moving vertically within the bubble plume.

As shown in Fig. ___ the net result of cooler water mixing with warmer water higher in the bubble plume is that the cold water initially entrained in the bubble plume does not return all the way down to the sediment interface from which it originated, but comes to equilibrium at an elevation some distance above the sediment/water interface. Unfortunately free rising air or oxygen bubble injection within the hypolimnion does not affect the sediment water interface because the internal circulation “cells” within the lake caused by vertically induced currents are confined to the higher elevations above the sediments. This problem is pictured schematically in Fig. ___.

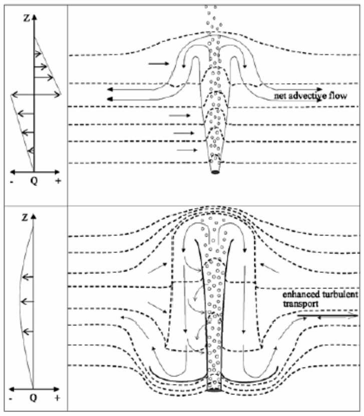
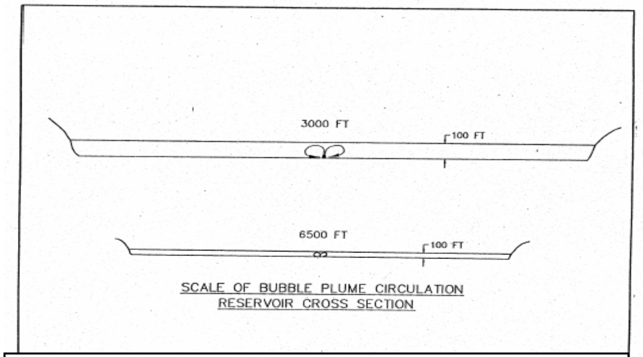


Figure 11. (top) Traditional plume model approach and (bottom) new model concept of plume behavior and short-circuiting in deep lakes (not to scale). Dashed line indicates constant temperature isopleths demonstrating near-field alteration. Left axis shows approximate far-field vertical compensation flow rate distribution (see Figure 12).



Circulation Pattern of Free Rise Bubbles

C. Salt Wedge Flow Oxygenation

If the salt wedge flows into Savannah Harbor are of significant importance then supplementation of D.O. at the mouth of the harbor would transport some of the D.O. into the harbor within the salt wedge tidal action. A superoxygenation station being fed salt water at the mouth of the harbor would exploit this type of circulation possibility.

V. Conclusions

The unique configuration characteristics and use requirements of a moderately deep harbor require sufficient oxygenation circulation to reach locally depleted ares as well as sediment layers without disturbing the sediments with their large oxygen demand or impeding ship channel traffic to maintain adequate D.O. levels throughout.

Innovative new technology which makes possible horizontal flow circulation for significant distances away from the superoxygenated discharge thus enlarging the zones of influence considerably, is an advance with much promise for meeting Savannah Harbor’s mixing and transport requirements.

In addition mobile barge self-contained oxygenation units, already installed successfully in Shanghai Harbor, Cardiff Bay and on the Thames River make possible timely intervention not hindered by stationary placement in the ship channel.

Section 6. Recommendations for Savannah Harbor Supplemental Oxygenation.

Criteria for Choice of Oxygenators

In evaluating D.O. supplementation technology, the following considerations must be critically addressed:

- O2 absorption efficiency
- unit energy consumption per ton of D.O. added
- D.O. concentration in side stream discharge
- capital cost of oxygenation system
- depth of water column
- location in water column where D.O. is needed
- target D.O. in harbor
- mixing requirements
- required spacing of D.O. supplementation stations
- placement outside the shipping channel
- availability of real estate
- availability of electricity

Life Cycle Cost Components

Appropriate technology for supplementation of pure oxygen is determined by the following three life cycle factors:

- present worth of the equipment – (purchase or rental)
- present worth of total oxygen required (therefore oxygen absorption efficiency becomes important)
- present worth of energy consumption per ton D.O. supplemented.

Life Cycle Cost of Speece Cone - $8,500,000

The Speece Cone oxygenation reactor and pump are estimated to be $85,000 per ton D.O. per day of capacity or **$8,500,000** for a 100 ton D.O./day system.

Calculation of Life Cycle of O2

Assume that:

- 100 tons/day of D.O. must be supplemented to the Harbor.
- oxygen is generated on-site by PSA units which cost $65,000 per each ton/day capacity and require 600 kwhr/ton of oxygen produced
- 50% utilization of the system per year
- $0.12/kwhr (diesel generated)
- 6% and 15 year life of the project.

Life Cycle Cost of On-Site Generation of Oxygen - $19,000,000

Since the oxygen cost is commonly the major economic component in the life cycle cost for supplemental oxygenation of rivers and harbors, this requires special consideration to select oxygen transfer devices which achieve high oxygen absorption efficiencies. A second aspect is that if the oxygen supplementation system is a mobile system with its own PSA oxygen generator, reduced oxygen absorption efficiencies are reflected in the need for greater oxygen generation capacity to account for the oxygen not absorbed. The Venturi aspirator oxygen absorption system incorporated on the Thames Bubbler is estimated to be about 65% efficient in its absorption of oxygen. Thus the required PSA oxygen generation unit must be 50% larger requiring 50% more power than if the system was 100% efficient in its oxygen absorption system.

The capital cost would be $6,500,000 for 100 ton/day PSA oxygen generation capacity. The energy consumption would be 60,000 kwhr/day for an equivalent cost of $7,200/day. Yearly amortization would be $6,500,000 x 0.1 = $650,000/y. Yearly energy cost would be 600 kwhr/ton x 100 ton/day x $0.12/kwhr x 180 day/y = $1,300,000/year. So the total yearly cost for generation of oxygen would be $1,950,000/year for 18,000 tons oxygen per year or $110/ton of oxygen produced.

The life cycle present worth of $1,950,000/year for O2 at 6% and 15 years (9.7) = **$19,000,000** for 100 ton D.O/day.

Implications of O2 Absorption Efficiency on Life Cycle Costs

The implications of oxygen absorption efficiency on life cycle costs are as follows for a 100 ton/day usage for 180 days per year for $110/ton O2 for 6% @ 15 yrs:

O2 Absorp. %	Ton O2/day Needed	Ton O2/day wasted	O2 wasted ton/yr	Present Worth $ of O2 **not** absorbed
100	100	0	0	0
90	110	10	1,800	1,900,000
80	125	25	4,500	4,800,000
70	145	45	8,100	8,600,000
60	165	65	11,700	12,500,000
50	200	100	18,000	19,200,000

This table indicates that O2 absorption efficiency has a considerable impact on life cycle costs of this project. Therefore selection of the oxygen transfer process is heavily weighted by its inherent absorption efficiency. Low O2 absorption processes will probably be cheaper than efficient ones on a capital cost basis, but will incur proportionately greater life cycle costs as the above table indicates.

Life Cycle Cost of Energy - $4,200,000

For a 100 ton D.O/day system that had a unit energy consumption of 200 kwhr/ton D.O. the daily energy consumption would be 20,000 kwhr/day for 180 days per year and 6% for 15 years (9.7). If the cost of diesel generated electricity is $0.12/kwhr then the daily cost would be $2400/day for 180 days/year = $430,000 /year multiplied by 9.7 SPWF = **$4,200,000.**

Off Channel Oxygenation Systems

The following generic oxygen transfer systems qualify for off channel use to supplement D.O. to Savannah Harbor:

Venturi
Pressurized Side Stream
U-Tube
Speece Cone

Comparison of U-Tube and Speece Cone

Of the four systems above, only the U-Tube and Speece Cone meet the economic criteria. Both the U-Tube and Speece Cone have comparable:

- O2 absorption efficiency - >80 to 90%
- Unit energy consumption per ton D.O. – 200 to 300 kwhr/ton D.O.
- Level of superoxygenation in discharge – 50 to 60 mg/L

Capital cost per ton D.O./day will be a deciding factor.

ADVANTAGES OF THE U TUBE TECHNOLOGY

The advantages of U-Tube oxygenation, which led to its selection for the Tombigbee River, were as follows:

- oxygen transfer occurs in a pressurized vessel
- high D. O. concentrations of up to 50 mg/L at 28°C
- high rate of oxygen transfer per unit volume of reactor, up to 5400 mg/L per hour, versus 100 mg/L per hour for conventional aeration tanks and
- efficient oxygen absorption of 80 to 90%
- unit energy consumption per ton of D. O. add was approximately 200 kWh per ton of D. O., which is low because head loss across the system is low even though oxygen transfer occurs at hydrostatic pressures up to 175 feet
- U-Tube prolongs the oxygen bubble contact time
- generates exceptionally high D. O. saturation concentrations, enabling supersaturation of D. O. in its discharge.

Tombigbee River

40,000 lb D.O./day

- provides pressurization of the oxygen gas bubbles by hydrostatic pressurization
- consumes negligible energy in contrast with the excessive energy consumption of pumped pressurized vessels which lose all of the input energy across the pressure throttling valve thus also potentially losing supersaturated D. O. concentrations by effervescence.
- requires no external pumping where the water being discharged is at 30 foot above river level
- minimizes stripping of dissolved nitrogen gas from the water with consequent nitrogen gas dilution of the oxygen composition of the bubbles because gas transfer is occurring in a pressurized vessel.

The U-Tube requires a caisson which is 175 ft deep and requires a bubble harvester to capture undissolved bubbles in the discharge for recycle back into the down leg. This is required to achieve the required O2 absorption efficiency.

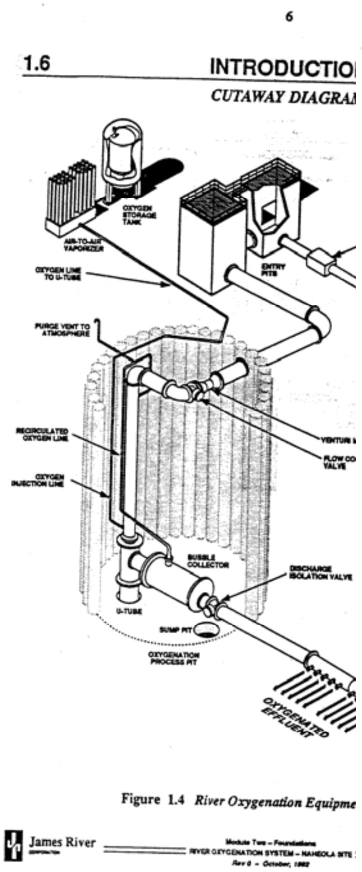
The Tombigbee River U-Tubes cost $10,000,000 for the entire project which included a 35 MGD gravity flow unit and a 125 MGD pumped flow unit. These two units transferred a combined total of 56,000 lb D.O./day. They were placed in a concrete caisson whose top exceeded the 100 year flood level and a diffuser was placed in the bottom of the river to disperse the superoxygenated discharge. I do not have accurate information on the cost of just installing the U-Tubes and their associated bubble harvesters. If it was half of the $10,000,000 total that would be $5,000,000 for 28 ton D.O. per day or $180,000 per ton D.O. per day of capacity. Unfortunately this specific cost information is not available.

For the pumped unit having 125 MGD flow a 10 ft diameter casing was excavated to a depth of 100 ft. and the lower 75 ft had an 8 ft diameter casing. Inside this casing a 7 ft diameter pipe served as the outer wall of the U-Tube and a 5.5 ft diameter pipe inside the 7 ft diameter wall served as the downcomer pipe. A 350 HP pump pulled water from the river and moved it through the U-Tube. The 35 MGD U-Tube was proportionately smaller.

A schematic diagram is shown of both the gravity fed to U-Tube which puts in 12,000 pounds of D. O. per day, as well as a schematic of the U-Tube where 125 MGD of water is pumped from the river through the U-Tube and then discharged back into the river with 50 mg/L of supersaturated D. O. concentration, resulting in 40,000 lb/day supplementation.

Field testing at James River of the U-Tube, which oxygenated the treated effluent from a James River mill, yielded the following observational operational results:

- discharge D. O. of up to 50 mg/L at 25°C in the water
- head differential across the U-Tube was 5.3 ft and
- oxygen transfer capacity of up to 16,000 pounds of D. O. per day and
- oxygen absorption efficiencies of 80 to 90% were realized.



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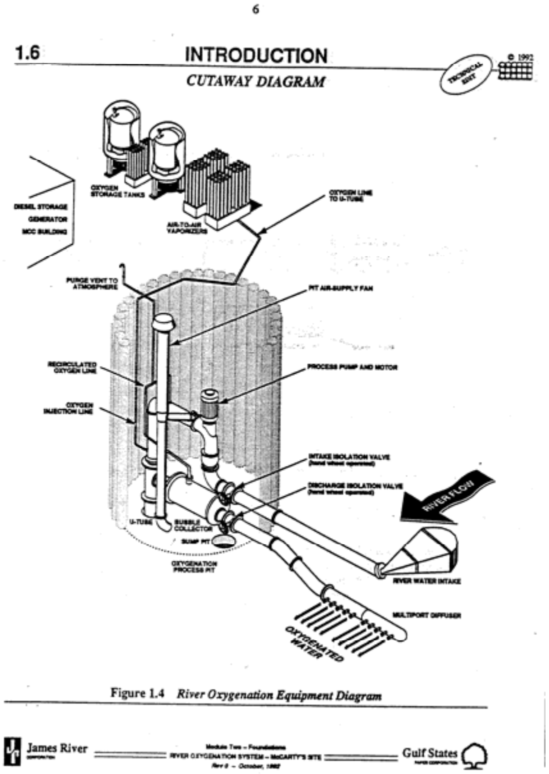
1.6 INTRODUCTIO

CUTAWAY DIAGRA

Figure 1.4 *River Oxygenation Equipme*

James River
Module Two – Foundations
RIVER OXYGENATION SYSTEM – NAHEOLA SITE
Rev 0 – October, 1992



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1.6 INTRODUCTION

CUTAWAY DIAGRAM

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Figure 1.4 *River Oxygenation Equipment Diagram*

James River
Module Two – Foundations
RIVER OXYGENATION SYSTEM – McCARTY'S SITE
Rev 0 – October, 1992
Gulf States

Advantages of the Speece Cone.

For application of the Speece Cone for supplemental oxygenation of Savannah Harbor, a main advantage is that no excavation costs would be required because the 50 ft depth of the harbor can be utilized.

The Speece Cone incorporates efficient oxygen absorption with low unit energy consumption per ton of D.O. discharged and achieves highly superoxygenated discharge levels. The Speece Cone can achieve O2 absorption efficiencies in excess of 90% while producing D.O. concentrations of 50 mg/L at unit energy consumption rates of <200 kwhr/ton D.O. if placed on the bottom of a 50 ft deep impoundment or harbor.

This device incorporates an inverted conical gas transfer vessel in which the water is introduced at the top of the cone, flowing in a downward direction. As the water flows downward its velocity decreases in proportion to the cross-section of the cone. Pure O2 is also injected into the cone and the resulting hydraulic turbulence creates a bubble swarm which has an exceptionally high oxygen/water interfacial area, which greatly enhances oxygen transfer.

By sizing the cross sectional area of the cone so that the downward velocity of the water slows to a point where it is less than the buoyant velocity of the bubbles within the cone, it is possible to retain the oxygen bubbles within the cone for prolonged periods of time, far in excess of the 100 seconds required for efficient oxygen absorption.

The pressure differential across the cone is rather small being primarily in proportion to the void volume of the bubble swarm within the cone. Thus the unit energy required to pump water through the bubble swarm is relatively small, and therefore the unit energy per ton of D. O. dissolved is also relatively small.

The concentration of D. O. that can be produced in the discharge is related to be depth of submergence or the hydrostatic pressure within the cone. Pressure enhances the oxygen transfer process. The deeper the cone is placed below the surface of the harbor, the higher the dissolved oxygen concentration produced in the discharge. Although the discharge D.O. increases in proportion to depth of submergence, the required pumping energy remains essentially constant, resulting in lower unit energy Kwhr/ton vs depth.

The cone discharges the highly superoxygenated sidestream back into the harbor in a horizontal direction through a diffuser with 2 inch diameter ports at port velocities of 10 to 20 ft/sec. An outstanding feature is that the equipment can be located outside of the shipping channel by directing its superoxygenated discharge perpendicularly across the ship channel.

In summary, a 12 feet diameter Speece Cone 15 ft tall placed 50 ft below the water surface will give the following results

- 60 mg/L discharge D.O.
- 34 cfs cone flow
- 12,000 lb D.O. per day dissolved
- 45 HP pump utilized
- >90% oxygen absorption achieved
- <200 kwhr/ton D.O. consumed depending on depth
- cost of units -$85,000/ton D.O./day ($500,000 per 12 ft diameter unit with pump)

The excellent results of this system (>90% O2 absorption efficiency) and low unit energy consumption (<200 kwhr/ton D.O. produced) occur in part because turbulence is confined to the inside of the cone with no bottom scouring. These

outstanding results are achieved without interfering with ship channel activity.

Self-Contained Mobile or Stationary Oxygenation Barge.

It is recommended that all municipal and industrial effluents be equipped with superoxygenation systems capable of adding D.O. concentrations equivalent to their effluent BOD_L concentration so that no D.O. resources from the harbor are consumed.

For supplying the oxygen demand of decaying vegetation, self contained barge mounted systems capable of supplementing 48,000 lb D.O./day to the harbor are recommended. Each unit would be comprised of 4 – 12 ft diameter Speece Cones each driven by a 45 HP pump. These oxygen transfer reactors would be suspended as far below the barge as possible to capitalize on the increased hydrostatic head. The D.O. in the discharge will be about 60 mg/L. This superoxygenated discharge can be placed near the bottom of the water column where it is needed most. The option is there to place it at any elevation in the water column. This will be rapidly diluted in the discharge diffusers which will be designed so that the discharge velocity and elevation above the sediments do not unduly disturb them resulting in exacerbation of the D.O. demand.

However with the intense turbulence generated by the propeller wake of numerous ships traversing the harbor, it would appear that the sediment/water interface is already continuously perturbed making the relatively minor turbulence caused by the oxygenated side stream a moot point by comparison. These oxygen supplementation systems could be permanently anchored any place within the harbor or be moved to any location within the harbor as needed. The most likely scenario is that some would be permanently anchored at a pier along the harbor where tidal action would be primarily used to move the oxygenated water away

A key consideration in supplementing oxygen to the harbor will be the availability of land at key locations defined by D.O. deficiency conditions within the harbor, upon which the oxygenation system could be placed. The availability of electricity is another consideration. Generally it is quite expensive to bring in electricity. So these two facets, the availability of the real estate in the vicinity of the place where the oxygen is needed and the availability of electricity brought to that location will be significant economic factors.

As has been done on the Thames River and the Shanghai Harbor mobile oxygenation systems, one possibility for Savannah Harbor would be construction of a barge mounted unit that would be able to supplement oxygen directly to the harbor. The advantage of a barge mounted unit, is that it does not require any real estate along the harbor. Another advantage is that it can either be tied up permanently at some location along the ship channel or it could be moved to various points as needed in the harbor where oxygen is deficient. This unit can be self-contained, with its own PSA oxygen generation source, which could be driven by an internal combustion engine that requires no electrical power be brought in. Furthermore, the pumps required to move water through the oxygen transfer vessel can be powered by combustion engine driven pumps. Thus, the barge units would only need to be supplied with diesel fuel. In some cases, propane driven pumps have been used to anticipate the possibility of a spill in the harbor. Propane with its volatile nature would not present a pollution problem if spilled into the harbor such as diesel fuel would.

Mobile Oxygenation Barge

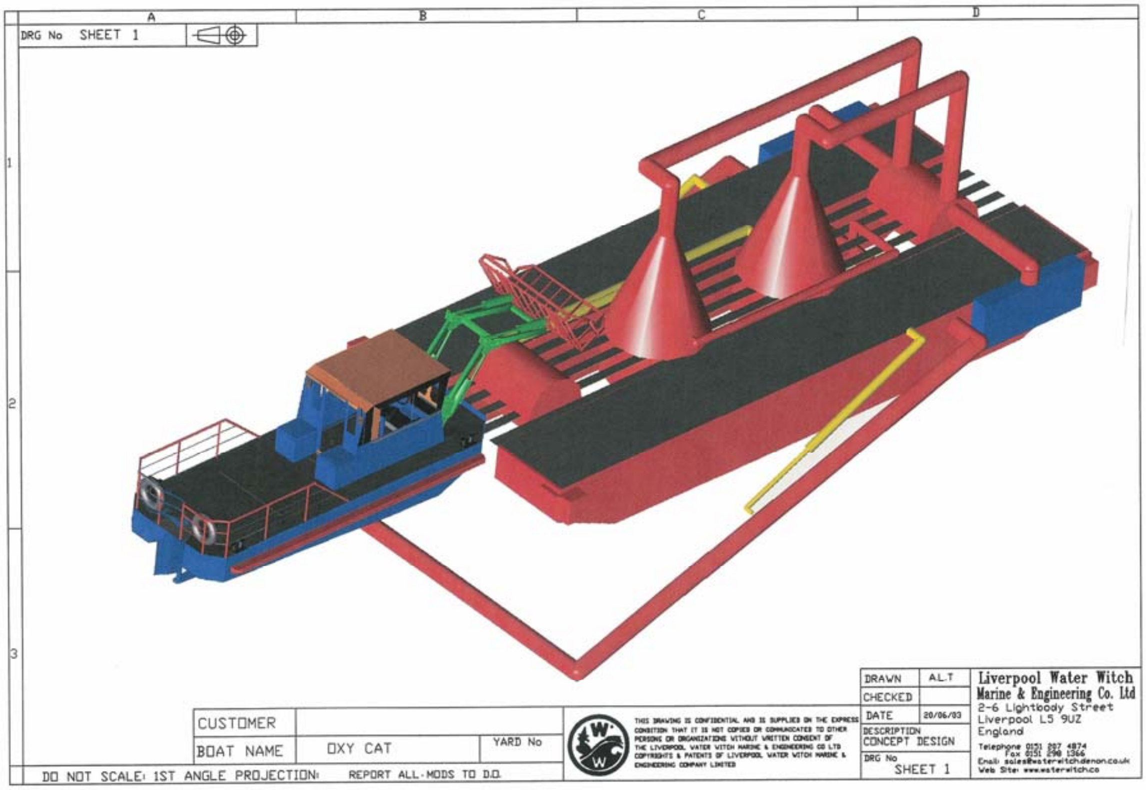
Mixing and transporting of the super oxygenated water within the harbor are key goals which must be achieved in a successful D.O. supplementation project. Oscillating tidal currents will be one of the main mechanisms which can be capitalized upon for movement of superoxygenated side streams away from the zone where they are generated. However a hydraulic model of water movement within the harbor would probably indicate some locations which will not have adequate transport of supplemented D.O. so as to meet compliance. Furthermore these D.O. deficient regions may change with flow and temperature conditions.

In such cases a logical solution would be to incorporate a means to deliver D.O. directly to the locations which are out of compliance. The concept of a self contained mobile oxygenation system could be used to address such deficiencies in tidal mixing effectiveness for effective transport of D.O. to all regions where needed.

A self-contained mobile oxygenation system would include on-board oxygen generation by pulsed swing adsorption or vacuum swing adsorption. This feature would avoid the safety concern of needing to store oxygen. Diesel or propane driven engines could either directly drive the oxygen generation system and pumps to move water through the oxygen transfer system or could generate electricity on board to power such components.

It would be advantageous to capitalize on the hydrostatic depth of the harbor for enhancement of oxygen transfer by placing the oxygen transfer reactor as far below the surface as possible. Of course there may be regions outside the main deep ship channel where the depths are much less deep that may require the aid of a mobile oxygen supplementation system.

The following Figures show schematics of a mobile oxygenation system. It would be capable of withdrawing denser water from the bottom of the water column, superoxygenating it and discharging it horizontally back at the same depth by means of an adjustable discharge boom. Sound insulation for the diesel could mitigate the noise pollution arising there from.



Placement of oxygen within the water column by a variable depth discharge diffuser system.

Recommendation

Speece Cone superoxygenation technology is recommended for remediation of the D.O. resources in Savannah Harbor based on cost, superoxygenation level, flexibility and mobility.