III. Dissolved Nitrogen Problems Associated with Deep Water Air Injection

A. Reaeration Coefficient (k2) Factors

It is often prematurely assumed that supersaturated gases will be stripped back down to saturation levels in a short distance as the water flows freely downstream. Gas transferred into or out of a river is generally characterized by a parameter called the rearation coefficient (k_2) in units of per day. The rearation coefficient is a function of the depth of the river and the energy dissipation rate. Energy dissipation, in turn, is a function of velocity and the slope or fall of the river. Therefore in a shallow river with a steep slope such as a mountain stream, the rearation coefficient is high, perhaps in excess of 10 per day, and D.O. and DN tend to approach saturation in relatively short distances.

However, hydropower discharges frequently feed deeper slow moving downstream reaches, which often have reaeration coefficients of less than 0.1 per day. For instance the Columbia River is pooled between dams for navigation purposes, and thus has minimal energy dissipation which is compounded by its considerable depth. Consequently in the Columbia River, D. N. values of 130% have been measured with very little decrease over distances of 50 to 80 miles downstream. One cause for this slowness of reaching equilibrium is the gradual warming of the water which increases supersaturation by approximately 2.5% per degree C. increase.

Therefore it is significant that stripping of supersaturated dissolved gases will be intolerably slow in deep harbors and thus cannot be considered as a mitigating factor to achieve compliance with water quality standards for D. O. and DN and /or for total gas pressure (TGP).

B. TGP and D.O./D.N. Ratios in Preventing Fish Mortality

When supersaturation was first recognized on the Columbia River, 110% dissolved nitrogen was adopted by several U. S. northwestern states and the National Academy of Sciences and Oregon adopted 105%, as the maximum standard. However it was later determined that gas bubble disease is related to TGP so at present the U.S. Environmental Protection Agency has established 110% TGP as the water quality criteria. This TGP standard replaces standards based on only dissolved nitrogen (U.S. EPA 1976).

Several studies show that a high dissolved oxygen pressure can reduce the potential of a given TGP to produce gas bubble disease (Rucker 1976; Nebeker, Bouck and Stevens 1976; Nebeker, Hauck and Baker 1979). Even though gas bubble disease is related to TGP rather than just dissolved nitrogen, the D. O./ D. N. ratio is important in determining the severity of symptoms and rate of mortality (Nebeker and Brett 1976). According to their study there was a significant decrease in mortality when the ratio of D. O./ D.N. was increased while holding TGP constant.

C. Need for a New EPA TGP Standard for Superoxygenation

Nebeker and Brett's finding raises a question as to the validity of the present day EPA water quality criteria of 110% TGP being applicable to both spillway discharges and hydropower discharges. It is crucial to differentiate the impacts of air entrainment in spillways and hydropower releases from oxygenation using pure oxygen. The former increases D.N. – the major component in gas bubble disease – while oxygenation with pure oxygen does not increase D.N. at all. These two types of configuration have characteristically different DO/DN ratios, which are a definite factor in fish response in mortality. Bouck previously stated that "a single numerical criterion is a simplistic approach, which can be defended only as a first step in a sequence, culminating in field verification."

As a case in point, two fish kills occurred below the Mactaquac hydroelectric station in New Brunswick, Canada in the summer of 1968. Gas bubbles were observed on the dead and dying Atlantic salmon and eels. Due to the opening of the automatic vacuum breakers at low discharge rates, the DO and DN were elevated to 80% oxygen and 120% nitrogen. Even though this total gas pressure of 112% was only slightly above the present EPA water quality criteria of 110%, it resulted in killing 10% of the 1968 up river run of Atlantic salmon (Mac Donald and Hyatt 1973). This author believes that a revaluation of the present EPA standard of 110% TGP should be undertaken to reflect more accurately N2 or O2 supersaturation as the actual cause of fish stress/mortality . The EPA TGP standard was developed in the context of hydropower and spillway discharges and was developed based on air aspiration at dams and spillways on the Columbia River. However it has been noted that spring water fed to fish hatcheries with diurnal heating that 103% TGP gave 100% kill over long seasons.

D. Gas Bubble Disease: Result of Several Causes

Lethality occurs only at high total gas pressures and is not the sole factor to be considered. Fish under stress can be in a weakened state, making them susceptible to bacterial infections and parasites (McLaughlin and Busch 1981). Elevated D.N. levels are always dangerous to the resident fishery.

Physical symptoms of gas bubble diseases in fish have been reported to be:

- emphysema
- lesions
- gil congestion
- popeye
- cardiac blockage by embolism

(Fickeisen and Montgomery 1978, Bouck 1980, Weitkamp and Katz 1980).

E. Dissolved Nitrogen Problems Associated with Air Injection

When air is introduced into a water column, both oxygen and nitrogen gas are dissolved. Fig. shows the projected D.N. increase when air was injected into a water supply reservoir in Germany. These are rather high D.N. concentrations. This figure indicates that the dissolved nitrogen in the plume of an airlift aeration device is increased from a background saturated level of about 16 mg per liter by an additional 9 mg per liter in the airlift plume, resulting in 150% dissolved nitrogen supersaturation in the discharge.

Injection of air with its 79% N_2 content into a harbor would result in both O_2 and N_2 dissolution in the water column. Natural waters are always 100% saturated with dissolved nitrogen (D.N.) in equilibrium with 0.79 atmospheres partial pressure of N_2, corresponding to about 16 mg/L at 20 ^oC and sea level. Aquatic life is not adversely affected by D.N. as long as it remains below ambient air saturation. However injection of air into the water column results in raising the D.N. above this level and can result in gas bubble disease.

The State of Michigan has also reported high mortality rates in fish hatcheries which incorporate deep aeration basins used for the purpose of D.O. enhancement. Therefore caution should be exercised to prevent such an occurrence when using air aspiration into turbine vents of hydropower dams. As mentioned previously oxygenation with pure O2 does not result in an increase in D.N.

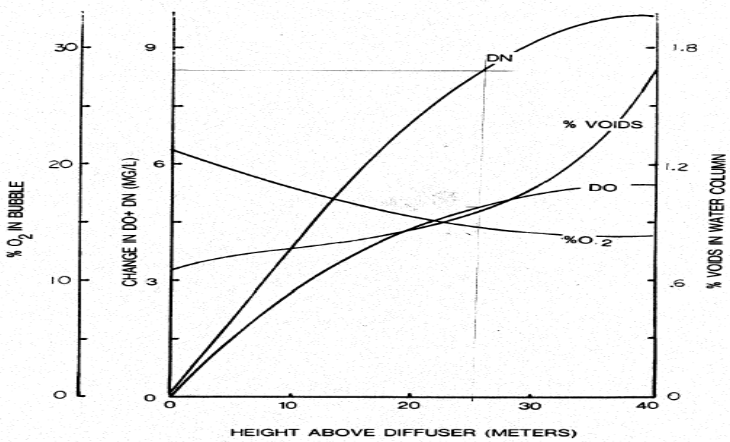

FIG. 1 GAS TRANSFER CHARACTERISTICS OF WAHNBACH SYSTEM

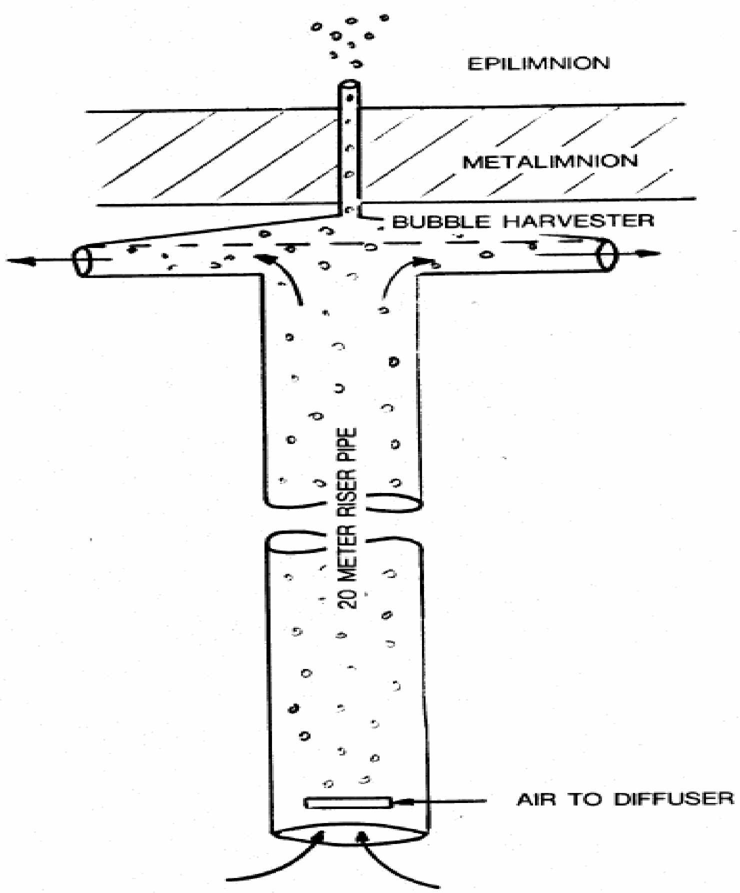

FIG. 2 PROPOSED HYPOLIMNION AERATION MODIFICATION

IV. Aeration System Evaluations

A. Chicago Canal Aeration System

The following section is quoted from a report on evaluation of the cascade aeration system used on the Chicago Canals.

Review of Chicago SEPA Stations Performance by Dr. Russ Brown

> The most well known waterfall facility for aeration of a river is the Metropolitan Water Reclamation District's side-stream elevated pool aeration (SEPA) stations along the Calumet Waterway Cal-Sag channel. This 17-mile long navigation channel (connecting the Des Plaines River with Lake Michigan is 225 feet wide, 9 feet deep, and is extremely slow moving. The low-flow condition in the channel is estimated to be about 1,200 cfs. The DO objective established by the Illinois Pollution Control Board is 3 mg/l. Each of the five SEPA stations are designed to lift about 400 cfs with 2-5 rotary or screw pumps about 12 to 15 feet and discharge over a series of 3-4 waterfalls (i.e., cascade). The number of pumps operated can be adjusted to match the ambient DO conditions to minimize electrical costs. The design assumption was that the waterfalls would increase DO to 95% of saturation. The SEPA stations were completed in 1993 at a cost of about $40 million.
>
> The Illinois State Water Survey (ISWS) conducted a 2-year measurement program following the construction and operation of the SEPA stations to determine the actual performance of the five stations for a range of ambient DO conditions and temperatures.
>
> They report (Butts *et al* 1998) that the cascades (3-4 waterfalls of 3-5 feet each) produced water that was more than 90% saturated with DO. A majority of the aeration occurred in the large screw pumps. A cascade of 3 waterfalls with a combined drop of 10 feet will likely provide a reaeration efficiency of 90%.
>
> The effects of the waterfall stations on the river DO were more difficult to detect (Butts *et al* 2000). Mixing of the waterfall water back into the channel occurred near the surface and the downstream channel measurements could not easily determine an increase compared with the upstream river measurements. Algae and macrophyte (i.e., aquatic plants) productivity and natural aeration caused the surface DO concentrations to fluctuate and made it more difficult to isolate the effects of the waterfall aeration. More attention should be given to mixing the aerated waterfall effluent back into the river.

B. San Joaquin Ship Channel Aeration Performance Evaluation

The San Joaquin River flows from Stockton, California toward the San Francisco Bay and is used for shipping. The current is slow moving, causing the reaeration rate to be quite low, resulting in D.O. deficiency. Note the low oxygen efficiency of the aeration equipment.

The following is quoted from a report by Dr. Russ Brown on the performance of this system.

> The manufacturer design documents suggested that these two sets of bubble-jets would each transfer 1,250 lb/day of oxygen. The depth of 25 feet suggested a maximum transfer efficiency of 20% for the oxygen dissolved from the bubbles into the water. The actual performance on September 26, 2001 was about 75% of the design value for the south jet (i.e., 925/1250 = 75% of design). This seems quite good considering that the DO deficit was only about 2 mg/l. The oxygen absorption would be greater at a higher deficit. The north bubble-jet was operating at less than 20% of the design value (i.e., 225/1250 = 18% of design). It is likely that the performance can be increased considerably by simply turning up the air flow rate to increase the bubble column upwelling and flow-away current. How much of this potential DO increment is transferred to the DSWC depends on the surface DO of the DWSC during the day.

Bubble Jet Aerators

> If the average DO increment measured at the railroad bridge is reliable, the overall efficiency of the Corps aeration device was about 30% of the design value (i.e., 740/2500 = 30% of design). However, because the air bubbles do not appear to be spread across the river channel, and a considerable amount of the compressed air is allowed to vent to the atmosphere, some design changes should be considered. It appears that a single 20 hp air blower (260 scfm) could produce an equivalent air bubble column from traditional diffuser heads (i.e. ceramic head or holes in pipe). The water jets with the two 15 HP jet pumps could be eliminated, and an equivalent amount of oxygen transfer from the upwelling currents could be achieved for less than 30% of the energy (i.e., 20 hp compared to 70 hp for current device).

A preliminary estimate of upwelling flow that could be generated from an equivalent air delivery rate to a single line diffuser can be derived from the equations presented above (Brown et al. 1989). Assuming the 260 scfm is distributed through a 10-m long diffuser, an upwelling flow of about 675 cfs of oxygenated water could be produced. Even with conservative assumptions that the oxygen transfer efficiency is the same between the line diffuser and jet-type aerator, this would represent a slightly greater amount of oxygenated water being distributed into the channel The upwelling equations suggest that similar entrainment of water could be generated without the need for a supplemental water jet pump and its associated power consumption costs.

Another possible design change would replace the air compressor with pressurized (i.e., liquid) oxygen gas, to increase the amount of oxygen dissolved by these relatively shallow bubble columns. The compressor power costs would be saved but the oxygen costs to satisfy the design (i.e., 2,500 lb/day) would be about $250/day. This aeration facility, if converted to an oxygen supply, might allow more than the current increment of 2,500 lb/day of oxygen to be added to the DWSC. The ability to remove the diffusers from the water during the winter and spring remains a very nice design feature of the Corps device. Its location along the side of the SJR channel is another very important design feature.

No measurements of supersaturation levels of D.N. caused by air injection 25 ft below the water surface were made.

V. Conclusions

With low target D.O. levels and inexpensive electricity rates, aeration equipment can suffice in some locations to bring water quality into compliance. However D.O. target levels above 4 mg/L and rising energy costs will preclude many aeration technology applications in the future and mandate replacement of some existing installations now in use.

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Section 4. Oxygenation Technology

4. Oxygenation Technology

I. Background

The unit energy consumption of a successful oxygenation system is relatively insensitive to the discharge D.O. up to about 70 mg/L, as shown in Fig. 2 (Speece, Khandan and Tchobanoglous). But recent developments in superoxygenation technology make possible highly elevated discharge D.O. concentrations economically achieved which solve many water quality issues.

Successful oxygenation of a surface water body is predicated on efficient dissolving of gaseous oxygen into water.   The specific design constraints for superoxygenation technology which must be achieved are:

- high oxygen absorption efficiency
- low unit energy consumption (kwhr/ton D.O.)
- side stream superoxygenation (50 to 100 mg/L) at reasonable capital cost
- retention of superoxygenated D.O. in solution

II. Comparison of commercial oxygen vs air as the oxygen source

A. Disadvantages of air as the oxygen source

It may appear counterintuitive to utilize commercial oxygen in raising D.O. concentrations when air is available free. There are several mitigating factors, however, which make the use of commercial oxygen more economical than air in most cases. For instance dissolving oxygen from air into the water involves considerable capital and operating costs. There are also some adverse effects associated with the use of air which are negated using commercial oxygen.

The use of air in contact with water under more than ambient pressure results in supersaturation of the water column with dissolved nitrogen gas with its potential adverse impact on fish. Air as the oxygen source also restricts the maximum dissolved oxygen concentration achievable in a sidestream, and therefore increases the required sidestream flow to achieve a given daily oxygen supplementation mass rate.

In addition the use of air necessitates almost an order of magnitude greater energy expenditure per ton of dissolved oxygen increase when compared to commercial oxygen use. Conventional aeration devices consume 1000 to 2000 kWh per ton of oxygen dissolved, requiring energy expenses of $0.05/kwhr or $50-$100 per ton of oxygen dissolved, with amortization of the capital adding still more cost. Commercial oxygen costs $40 to $200 per ton in bulk, depending on site-specific conditions. Commercial oxygen can be dissolved even in stratified water columns and generally becomes more economically competitive when the target dissolved oxygen goal exceeds 4 to 5 mg/L.

B. Advantages of pure oxygen as the oxygen source

Equipment is now available for superoxygenation (using pure oxygen) to achieve discharge D.O. concentrations of 50 to 100 mg/L. Contrary to a popular misconception, these high D.O. concentrations of less than 100 mg/L do not spontaneously effervesce, but are kept in solution. It is now possible to pull a small sidestream from a river, superoxygenate it, and dilute it back into the main river to satisfy D.O. deficiencies *without treating the entire river*.

To minimize the fraction of river flow thus moved through the oxygenation system, the D.O. concentration achieved must be maximized. This necessitates the use of commercial oxygen, either liquid oxygen (LOX) trucked in or high purity oxygen (HPO) produced on site. Commercial oxygen can be dissolved at elevated pressures without the adverse effects of nitrogen gas supersaturation, which occur when using air under pressure. Use of commercial oxygen allows exceptionally high D.O. concentrations to be produced in the oxygenation system effluent.

Advantages of superoxygenation treatment, when compared to aeration, pollutant reduction, or low flow augmentation in raising the D.O. levels include:

- no measurable negative impact on water quality and the receiving water
- no dissolved nitrogen (DN) supersaturation problems
- a smaller footprint for the oxygenation installation
- less energy consumption
- higher sidestream D.O. levels of 50 to 100 mg/L achieved and kept in solution
- wider spacing of oxygen supplementation stations
- more practicality than tertiary removal of BOD
- less cost than aeration if the dissolved oxygen target exceeds 5 mg/L and electrical costs exceed $.05 per kilowatt-hou

Highly supersaturated D.O. concentrations are possible if special provision is made to prevent effervescent loss before dilution with the bulk harbor water. This makes it possible to supplement the desired oxygen tonnage into a relatively small side stream, minimizing the size of the oxygenation system and associated pumping requirements, and thus increasing the required spacing between oxygenation stations.

A good system for transferring oxygen from air will probably be a poor system for transferring pure oxygen into water. Air dissolution systems are designed to minimize the unit energy consumption and have low O2 absorption efficiencies, because the air is available free. Conversely, a good oxygen absorption system must achieve high O2 absorption efficiency, because the cost of oxygen is the dominant Life Cycle Cost component and the cost of energy consumption per ton is minor (i.e. 200 to 500 kwhr/ton D.O.), being only about 10 % of the oxygen cost.

Even pure oxygen is sparingly soluble in water. In order to assure efficient absorption of pure oxygen in water two requirements must be met:

1) the oxygen gas must be maintained in contact with the water for a prolonged period of time to achieve efficient oxygen absorption
2) dissolved oxygen stripping from the water into the oxygen bubble must be minimized

Since the water is initially saturated with dissolved N2 from being in contact with air, this dissolved N2 will partition back into the pure oxygen bubble. Consequently the partial pressure of O2 in the bubble will be reduced progressively below its initial 100% purity. This in turn will lower the D.O. saturation concentration as well as the D.O. deficit. Higher pressures inside the oxygenation system reduce the stripping potential of nitrogen gas dissolved in the water into the gas phase and therefore tend to reduce dilution of the pure oxygen feed by stripped nitrogen gas.

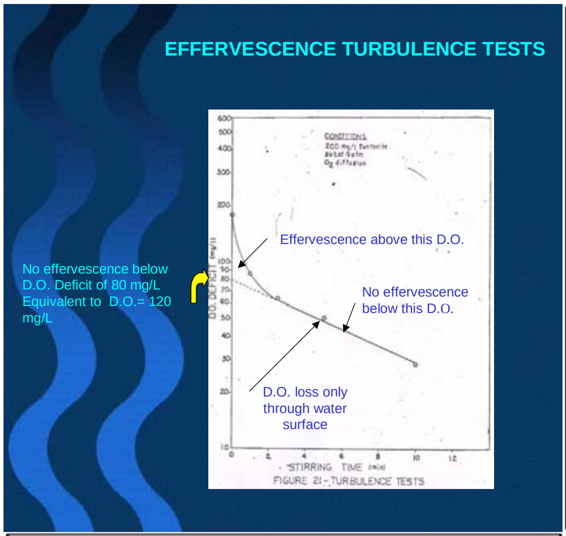
C. Effervescence

At steady state the concentration of D.O. in water will eventually reach that concentration which corresponds to saturation in contact with the gas phase. However the time to reach steady state can be quite prolonged. For instance the Columbia River flows for 80 miles at 130% supersaturation of dissolved gas and loses very little in transit. Of course the rate at which D.O. in undersaturated water reaches equilibrium is the same as the rate at which supersaturated D.O. reaches equilibrium. This is directly a function of the reaeration rate, k2, of the river. Slow moving, deep rivers have very low rates of reaeration while fast moving, shallow rivers have high rates of reaeration. The very low rate of gas exchange at the surface of Savannah Harbor is perhaps the reason for its chronic low D.O. concentrations. Conversely if a gas transfer device were used in the harbor which could raise the D.O. to 10 to 20 mg/L in a restricted region where it was produced, there would be negligible loss to the atmosphere.

In laboratory tests, it has been shown that the D.O. in water can be raised to 120 mg/L (D.O. deficit of 80 mg/L) using pure O2 under pressure and no spontaneous effervescent loss of this high concentration of D.O. will result upon depressurization of the system. This is shown in the accompanying Fig. ___. Furthermore the D.O. can be raised to as high as 250 mg/L using pure O2 under pressure and 90% of this can be retained in solution if it is diluted rapidly with water having a D.O. of less than 10 mg/L. In a third experiment in which water was highly superoxygenated to over 250 mg/L D.O. with pure O2 under pressure, if no care was taken to dilute it rapidly and spontaneous effervescence was allowed to occur, the residual D.O. after all effervescence had ceased was approximately 150 mg/L (380% saturation for pure O2).

These observations are corroborated by results from dissolved air flotation systems. DAF units operate the gas saturation vessel at about 60 psig which is 5 atmospheres absolute or about 400 to 500% saturation in the discharge. If the gas saturation reactor is not operated this high, then relatively little gas effervesces when it passes through the exit throttling valve.

The 45 – 50 ft depth of Savannah Harbor can be utilized advantageously for depressurization of pressurized superoxygenated side streams. The theoretical dissolved oxygen saturation concentration for pure oxygen at a 45 foot depth is 90 mg per liter. Since spontaneous effervescence does not occur below about 250 % of dissolved oxygen saturation when using pure oxygen it would thus be possible to raise the dissolved oxygen to about 2 1/2 times the 90 mg per liter of saturation i.e. 225 mg/L D.O. without the problem of effervescent loss of dissolved oxygen when it leaves a pressurized oxygen transfer vessel.



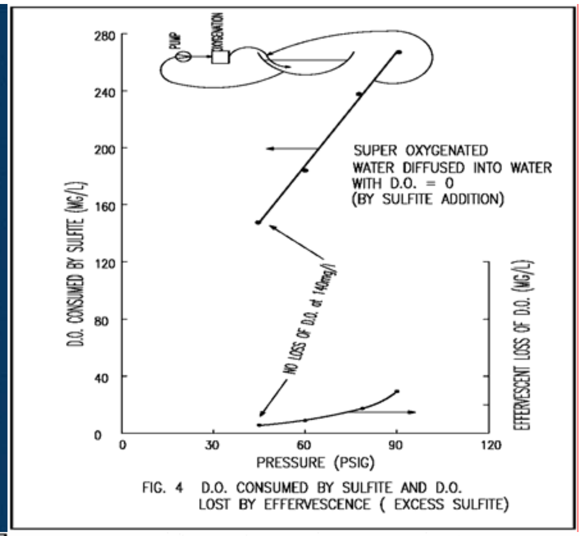


FIG. 4 D.O. CONSUMED BY SULFITE AND D.O. LOST BY EFFERVESCENCE (EXCESS SULFITE)

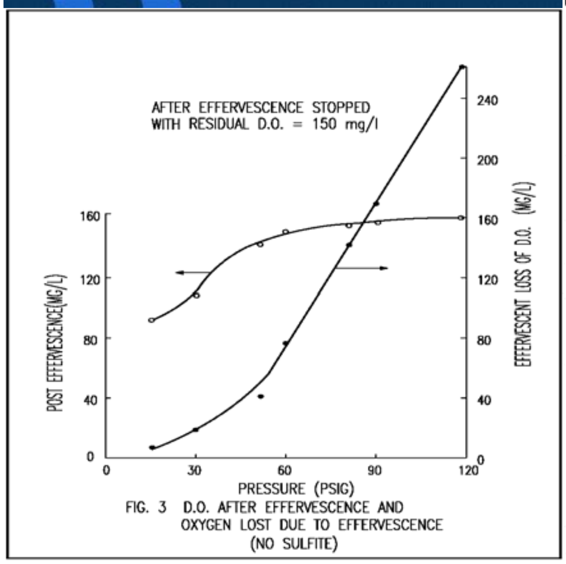
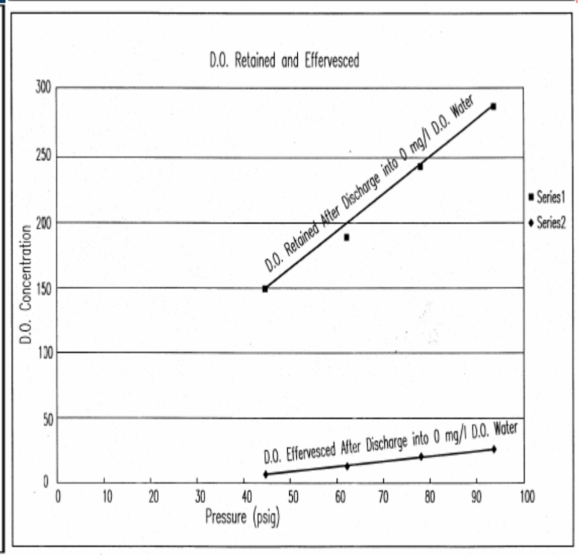


FIG. 3 D.O. AFTER EFFERVESCENCE AND OXYGEN LOST DUE TO EFFERVESCENCE (NO SULFITE)



D. Types of Oxygen Absorption Technology

Pure oxygen absorption systems are generally grouped into the following categories:

- Jet/Venturi Aspirators
- Soaker Hose
- Contained Atmosphere Surface Splashing
- Side Stream Pressurization
- U-Tube
- Speece Cone

E. Pure oxygen source advances

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

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

There is generally a trade-off between equipment cost and oxygen absorption efficiency. At low oxygen absorption efficiency the cost of equipment may be insignificant but the present worth of 'Oxygen Not Dissolved' may be large. An example of a low capital cost system with low O2 absorption efficiency would be injection of gaseous O2 through diffusers in waters with depths of less than 60 to 80 ft. Another example is a Venturi system which shears the bubbles to small diameters but depends on their rise up through the water column for most of the absorption. Thus shallow depths result in lower oxygen absorption efficiency for such a system.

Optimal high oxygen efficiency and minimal energy expenditure must be incorporated into the design of the oxygenation system adopted. Pressurized systems are desirable for producing superoxygenated D.O. concentrations in the discharge, but it is considerably more energy-efficient to achieve pressurization by hydrostatic head than by pumped head. Generally the unit energy consumption is < 400 kwhr/ton D.O. having a concentration of D.O. of >50 mg/L if the natural hydrostatic head is the means of pressurization vs the case where the pressurization is achieved by pumping against a throttling valve in the discharge line.

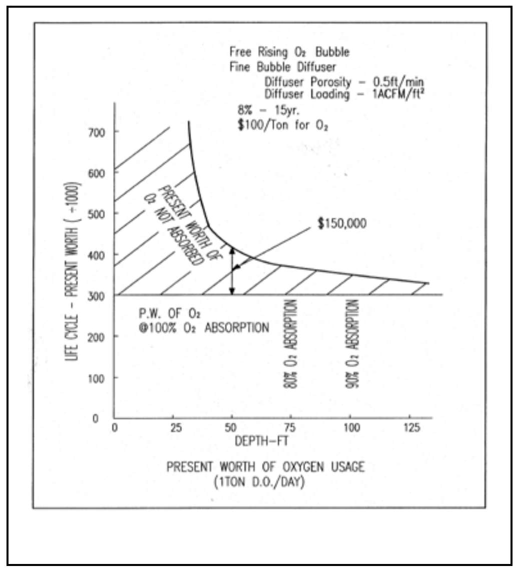


Fig. Present Worth of Oxygen

A superoxygenation device used in a harbor must be capable of highly superoxygenating a sidestream so that the amount of water to be treated is proportionately smaller. But this system must be located where the oxygen is needed. The Praxair ISO has a small zone of influence. This means that the modules have to be placed within the shipping channel involving many individual units with their electrical power lines strung across the surface area of the shipping channel.

Recent developments in molecular sieves and pulsed swing adsorption (PSA) technology for producing gaseous high purity oxygen (HPO) allow a practical and economical scale-down to capacities of < 1000 lb. O_2/day. PSA oxygen generators are much less complicated than cryogenic oxygen units because they require only a conventional air compressor, an air preparation package to remove water vapor and hydrocarbons from the feed air and molecular sieve beds. In addition there is no on-site storage of oxygen as is the case when using liquid oxygen (LOX).

Vacuum PSA (VPSA) units are as energy efficient as cryogenic oxygen consuming <500 kwhr/ton O_2 for delivery pressure of 0 to 2 psig. The capital costs also are competitive at about $70,000 per 1 ton O_2/day using the PSA system. This capital cost is generally flat over the O2 production capacity of 1 to 40 ton/day. Oxygen purity is 90 to 95%. VPSA systems are operationally more attractive than PSA. For smaller oxygen users, however, the LOX tank rental cost can be almost as much as the cost of the LOX itself.

III. Evaluation of Types of Oxygenation Systems

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

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

Praxair ISO

Praxair Company markets an oxygen transfer system which consists of a floating device which has a down pumper. There is also a large diameter shroud at the top which captures fugitive bubbles from the system. The down pumping device moves water downward and entrains gas from the headspace into the down flowing water. In this manner the oxygen enriched bubbles are moved down through the water in the downward plume and then the bubbles rise back to the surface as they migrate outside the downflow plume. As the oxygen bubbles rise they are captured as they exit the water by the shroud at the top. This mechanism satisfies the contact time requirement for efficient absorption of high purity oxygen because the bubbles are kept in contact with the water for over a hundred seconds. The pump works under very little head, requiring very little power to move the water in a downward direction.

This device achieves high oxygen absorption efficiency with a capacity of over 90% oxygen absorption efficiency. It also entails low unit energy consumption per ton of oxygen dissolved. However it is not able to raise the dissolved oxygen in a sidestream to more than about 10 mg/L of dissolved oxygen because the Praxair device operates under ambient pressure.

The downward pumping of the water drags bubbles down approximately 10 feet from which they then rise back to the surface. Thus the bubbles are under a maximum of about 1.3 atm absolute of pressure which corresponds to only about 10 foot below the surface in a harbor.

Fig. Aire Liquide Surface Oxygenator

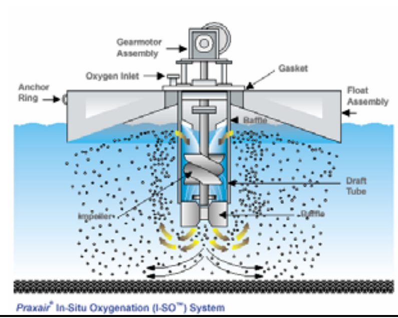


Fig. Praxair ISO Schematic

Fig. Praxair ISO Photo

The performance characteristics of the Praxair ISO system are:

- oxygen absorption efficiency is related to depth of water column
- unit energy consumption – 200 kwhr/ton D.O.
- cost of units - $/ton D.O./day capacity (rental $1500/month per unit)
- 5400 lb D.O./day per unit
- 25 Kw pump / unit

Venturi Systems

According to the Venturi principle of oxygen absorption, water is pumped at a high velocity through a Venturi throat section into which high purity O2 is aspirated. Due to the high velocity there is a high degree of shear, which results in the production of very small bubbles forming a high gas/water interface to be generated by the production of very fine bubbles in the throat of the Venturi.

A major drawback is that since the residence time within the Venturi is very short, even though the bubbles are tiny and have a high gas/water interfacial area, the brief contact time precludes efficient absorption. Since these microbubbles are not absorbed in the Venturi they remain in the discharge of the jet where some additional oxygen absorption takes place as the jet containing the microbubbles enters the bulk of the liquid for additional oxygen absorption. But this phenomenon causes the absorption efficiency of any Venturi device to be dependent upon the following factors:

- proper depth of the water column into which the oxygen is being absorbed
- appropriate energy input into the throat of the Venturi
- adequate relative rate of oxygen injection to water flow through the Venturi
- amount of velocity in the throat of the venture
- correct rate of entrainment of the bulk liquid after the water bubble mixture leaves the throat of the Venturi
- efficiency of oxygen dissolution in the bulk liquid
- overall target dissolved oxygen level for the entire system

Oxygen absorption efficiency is increased by deepening the water column, lowering the O2/water injection rates, and lowering D.O. in the water column.

Venturi systems produce oxygen absorption efficiency in the range of 60% and the unit energy consumption per ton of dissolved oxygen is in the range of approximately 1000 kWh per ton of dissolved oxygen. These systems are not able to transfer oxygen into water favorably, producing a discharge of only about 10 mg/L using high purity oxygen. Consequently the required spacing between the supplemental oxygenation units in the system is relatively short. However they could be located at the edge of the shipping channel and discharge their high velocity jet perpendicularly into the shipping channel.

In the evaluation of any Venturi type oxygen transfer system, the four key criteria for evaluation of performance which must be considered are:

- oxygen absorption efficiency
- unit energy consumption per ton of dissolved oxygen
- level of dissolved oxygen which can be achieved in the discharge
- relative spacing between the supplemental oxygenation units within the harbor.

O2 absorption efficiency increases as the relative O2/water ratio decreases, thus reducing the mass rate of D.O. addition per module. Likewise the unit energy consumption increases because the input HP remains constant.

Vendors which utilize the Venturi aspiration principle to achieve absorption of high purity oxygen include Air Products, Mazzei and Linde (similar technology - see photo).

Air Products: Oxy Dep

Venturi aspirators are utilized by these vendors as the oxygen dissolving systems. Water is pumped through a venturi at high velocity and oxygen gas in introduced at the throat. The venturi per se is not an oxygen absorber, but a high turbulence zone. Due to the high velocity/turbulence, the oxygen bubbles are sheared into very small diameters having high gas interfacial area. This enhances oxygen transfer primarily after the water enters the water column. Thus oxygen absorption efficiency is related to the depth below

Fig. Venturi Aspirator Throat

Fig. Air Products Oxy Dep

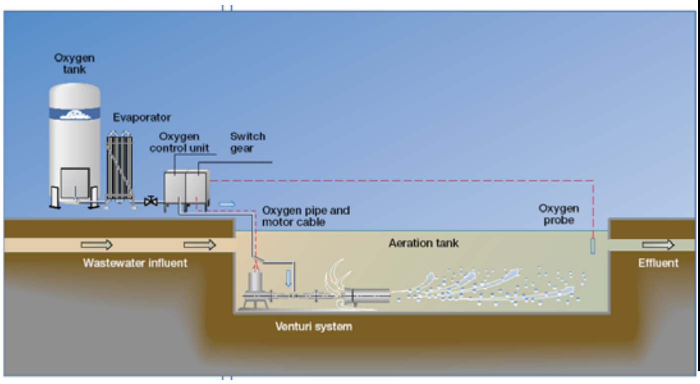


Fig. Venturi Oxygenator Schematic

Fig. Linde Venturi Oxygenator

the surface at which the venturi discharges. The information needed to evaluate the performance of a venturi aspirator oxygenation system is:

- oxygen absorption efficiency for jet/Venturi aspirators injecting pure oxygen over a wide range of oxygen feed rates
- oxygen absorption efficiency as a function of depth of water column
- corresponding unit energy consumption – kwhr/ton D.O.

- cost of units - $/ton D.O./day capacity

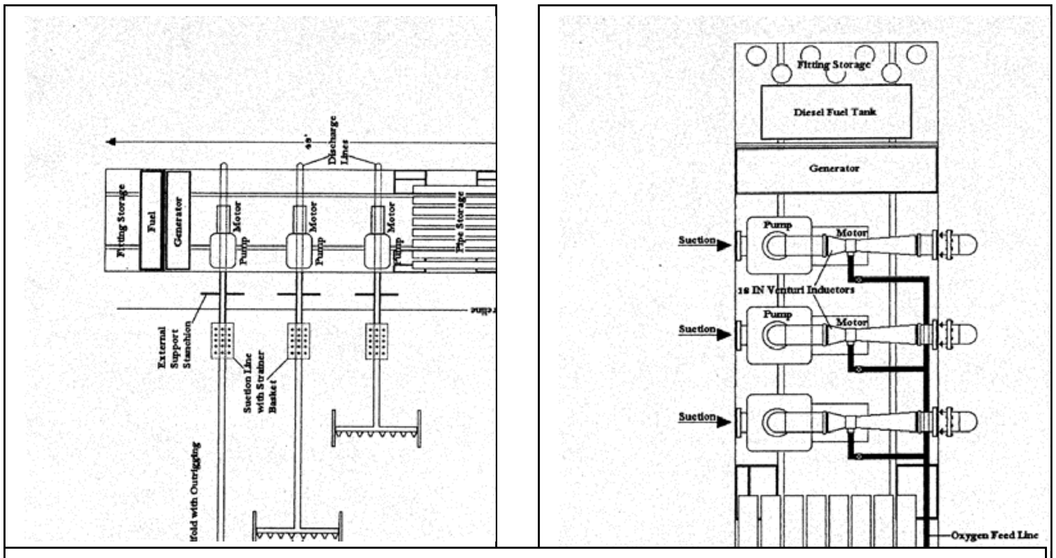


Fig. Mobile Venturi Oxygenator Schematic

Oxygen Bubble Injection

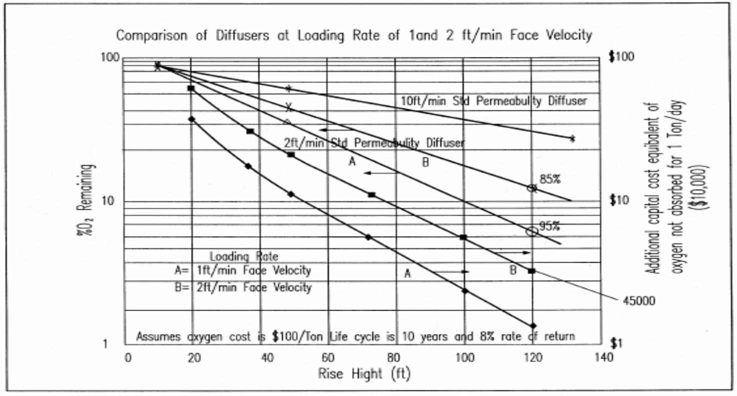
In the past high purity oxygen has been injected directly into various water bodies, but typically inefficiently. The issue is the difficulty encountered in absorbing oxygen into water efficiently at various depths. Table III shows oxygen absorption efficiencies for oxygen injection as fine bubbles associated with a range of depths are indicated. Fig. ___ shows % oxygen remaining vs bubble rise height.

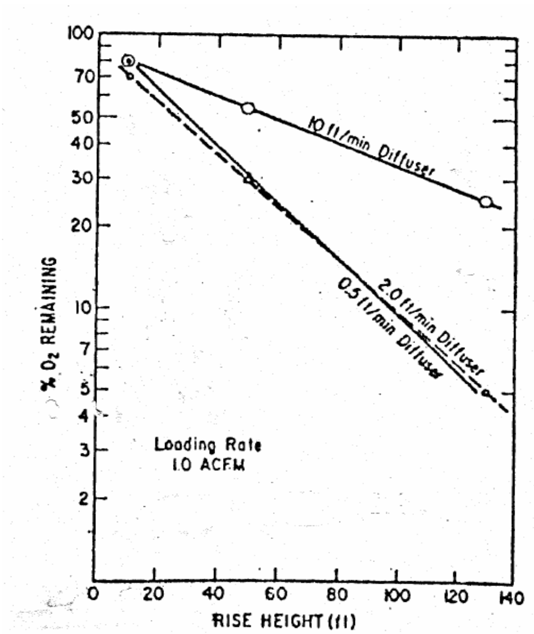
Field evaluation of the O2 absorption efficiency achieved by injection of fine bubbles ~2 mm diameter, into various depths of water columns was made in Clark Hill Reservoir in 1978 and the results are shown in Table III.

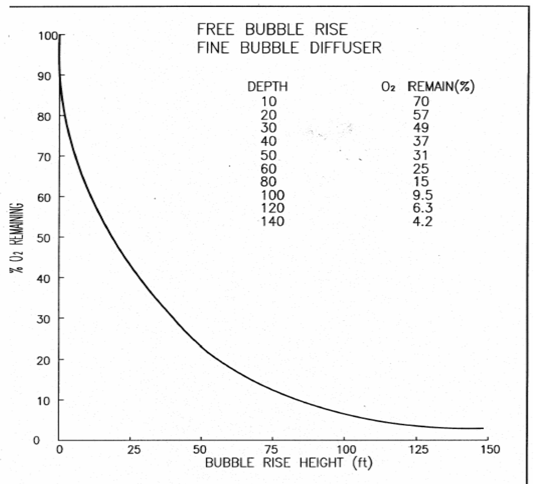
Table III Oxygen absorption efficiency from free rising oxygen bubbles in a 140 ft deep impoundment

Depth-ft	Oxygen Absorption Efficiency-%
10	20
20	45
40	62
60	78
80	85
100	90

Vertically induced flow from a bubble plume has a horizontal recycle cell zone of influence of about 4 times the bubble rise height within the hypolimnion. Thus for a hypolimnion depth of 100 ft, the oxygenated water would distribute itself within a cell of







at most only 400 ft diameter around the bubble source axis. On the other hand although vertical circulation is hindered by density gradients due to temperature, horizontal momentum of a cold-water inflow (which encounters negligible density differences) has been observed to travel the entire 45 miles length of a run-of-the-river impoundment at Clark's Hill Reservoir in the Savannah River.

Practically it may be of significant benefit in extending the zone of influence within the hypolimnion of the highly oxygenated sidestream to install low speed large diameter impellers directed in the line of flow from the discharge. This boost in momentum after a month of operation potentially could double the effective distance to 4-miles to which the oxygenated water is transported.

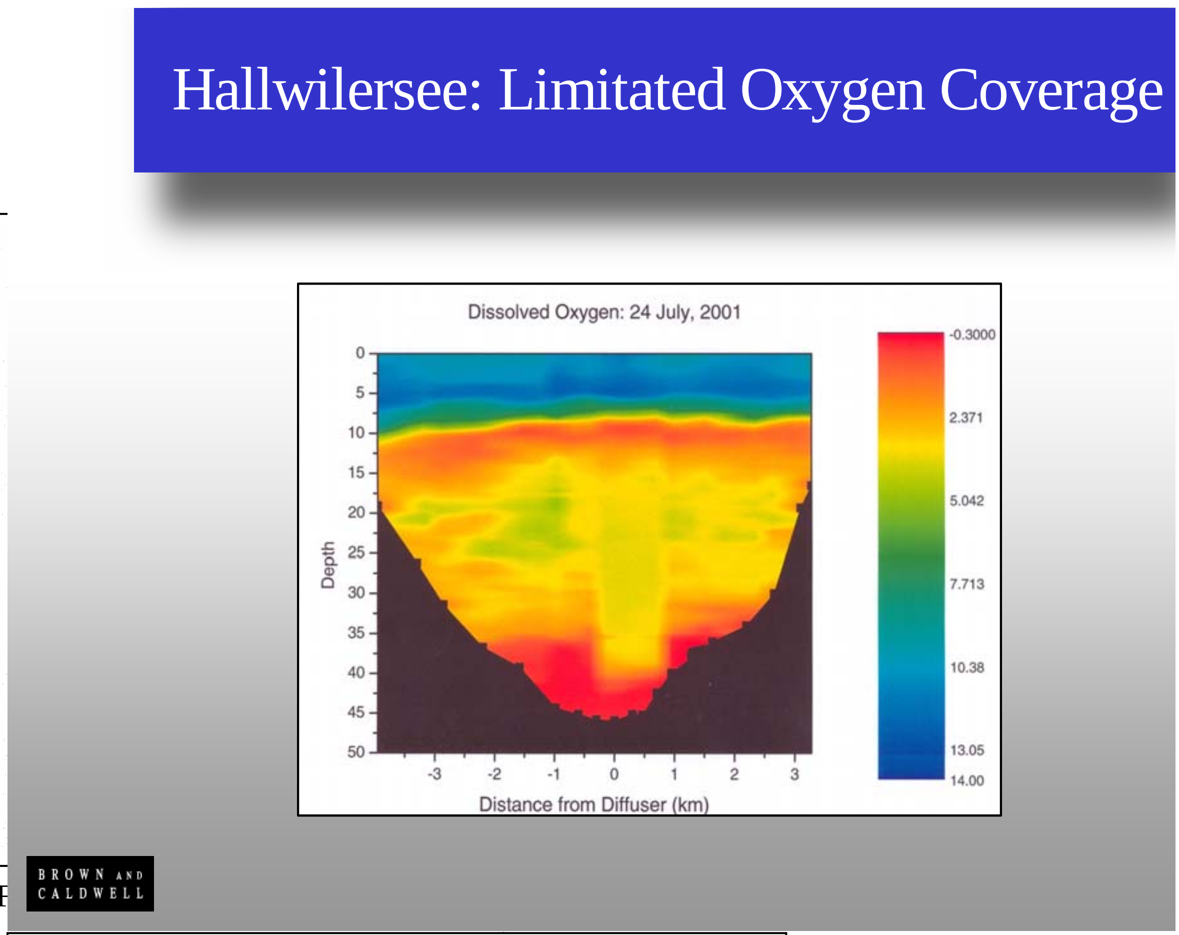
Figs. ___ and ____ demonstrate graphically the inability of free rising oxygen bubble plumes to oxygenate the zone at the sediment water interface. Due to the nature of the mixing in the free rising bubble plume, oxygen supplemented water always comes to equilibrium at some distance above the bubble diffuser. For instance in Lake Hallwilersee in Switzerland, using a fine bubble diffuser fed with pure O2, there is a 4 kilometer zone of sediment water interface which is not supplemented with D.O.

Soaker Hose

The so-called soaker hose oxygen transfer technology utilizes porous tubing similar to the tubing that is used in landscaping that allows water to escape slowly from the hose. The porous nature of the hose is utilized for absorption of high purity oxygen by placing the hose in the bottom of an impoundment and pressurizing it with pure oxygen. A series of feeder hoses and weights are incorporated to anchor the system to the bottom of the impoundment. Since the soaker hose system is a linear diffuser, its operational performance is dependent on the following principles.

- O2 unit loading rate (0.015 to 0.12 scfm/ft – 1.8 to 14 lb O2/ft/day)
- % O2 absorption vs depth
- vertical circulation pattern (not horizontal)

All of the oxygen transfer takes place as the bubbles diffuse from the soaker hose and freely rise up through the water column. Therefore the oxygen absorption efficiency is very much related to the oxygen loading rate on the soaker hose or ft^3 O_2 per min per foot of hose. At low oxygen loading rates relatively smaller bubbles are formed, whereas



D.O. Distribution from Fine Bubble Diffusers in Swiss Lake – Note no D.O. at sediment interface below diffuser

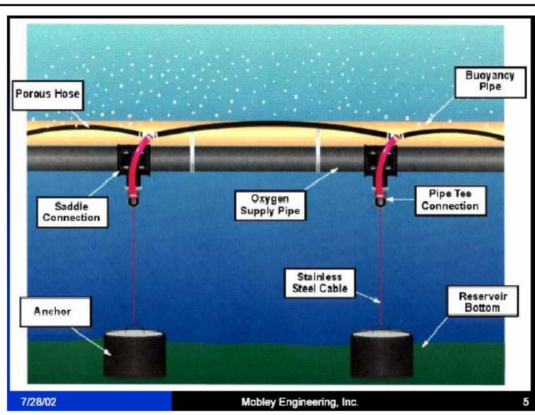
when the oxygen loading rate increases, the relative diameter of the bubbles rising from the soaker hose also increases. Thus at low oxygen loading rates fine bubbles are generated but at high oxygen loading rate relatively larger oxygen bubbles are generated. Since oxygen absorption efficiency in free rising bubbles is related to the size of the bubble, the oxygen absorption efficiency deteriorates as the oxygen loading rate increases.

Another mitigating factor is that the oxygen absorption efficiency is also very much related to the depth of the water column in which the soaker hose is placed. The oxygen absorption efficiency versus water column depth takes on a characteristic pattern, as shown in Fig. __ . Thus to achieve an oxygen absorption efficiency of over 80%, it is necessary that the soaker hose be placed in water columns that are in excess of about 100 feet. Since Savannah Harbor is approximately 50 ft deep, only relatively low oxygen absorption efficiency would result using soaker hose technology. O2 loading rates might need to be reduced by a factor of 10 to achieve more efficient absorption but such a reduction would require 10 times the lineal feet of soaker hose to transfer a given tonnage of O2 in more shallow water columns.

A second disadvantage of soaker hose technology for oxygen transfer in Savannah Harbor is that the soaker hose would have to be placed within the main channel and therefore be subject to the high turbulence of all of the propellers of the large ships traversing the channel.

The installed cost for soaker hose installation is reported to be about $50/lineal foot. In some installations the cost estimate has been as high as $75/ft. The O2 loading rate is controlled by the depth of installation. In order to achieve 90% O2 absorption in 50 ft of water, the O2 loading rate would have to be reduced to <2lb O2/ft/day. At $50/ft installed cost, this would be $50,000 capital cost per ton D.O./day.

No experimental mass balances are available to determine O2 absorption efficiency as a function of depth and O2 loading rate per lineal foot. Claims for O2 absorption efficiency are based on a computer model that was calibrated by air, not O2



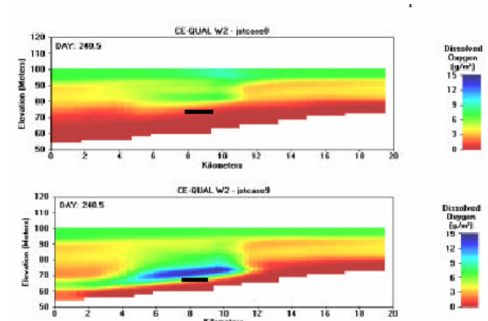


Figure 8: DO Predictions for Different Diffuser Elevations at J. Strom Thurmond

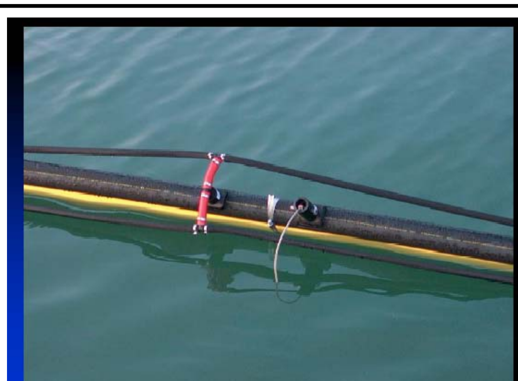


Fig. Soaker Hose Schematic, D.O. Placement and Photo injection, in a 14 meter deep tank.

Speece Cone Oxygenator

The Speece Cone oxygenator incorporates efficient oxygen absorption with low unit energy consumption per ton of D.O. discharged and achieves highly superoxygenated discharge levels. Speece Cone technology can achieve O2 absorption efficiencies in excess of 90% while producing D.O. concentrations of 50 mg/L at unit energy consumption rates of <300 kwhr/ton D.O. if placed on the bottom of a 50 ft deep impoundment or harbor.

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 (see Fig. __________). 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. This type of diffuser accomplishes two crucial functions:

- the dilution of the D.O. in the highly oxygenated sidestream
- the transport of this oxygenated water horizontally

Even though the cone discharge is highly oxygenated (50 mg/l) it is not above saturation level for its hydrostatic pressure and therefore has no effervescence potential. The D.O. is diluted down to below approximately 10 mg/l within a short distance of the discharge ports.

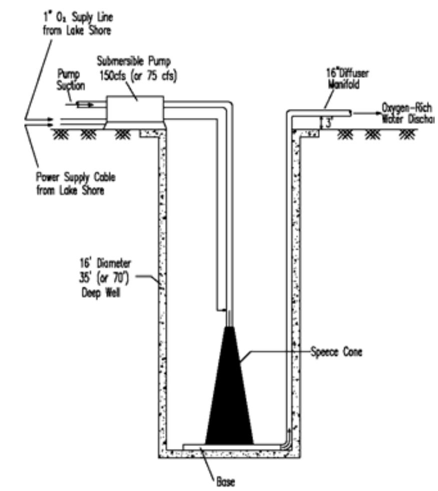
This device incorporates an inverted conical gas transfer vessel in which the water is introduced at the top of the cone, flowing in a downward direction. As the water flows downward its velocity decreases in proportion to the cross-section of the cone. Pure O2 is also injected into the cone and the 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. This feature also greatly 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.

Oxygen transfer is enhanced by pressurizing the oxygen transfer reactor. This allows the achievement of higher dissolved oxygen concentrations in the discharge. Higher oxygen concentration in the discharge, however, has the disadvantage of also consuming more energy per ton of D. O. absorbed. Typically the unit energy consumption per ton of D.O. added is approximately 1000 kWh per ton of D.O. absorbed, if the oxygen transfer takes place under pumped pressurized conditions. However, if placed in an excavated caisson (see Fig. ___) the gas transfer vessel is statically pressurized by the hydrostatic head without the need for pumping against a back pressure throttling valve energy. The water simply flows down into the gas transfer reactor and back out, achieving natural hydrostatic pressurization.



Speece Well Oxygenation System

If a deep caisson is unavailable and pressurization by pumping against a back pressure throttling valve is required, a proprietary system of oxygen transfer is available to recover the energy of the water leaving the pressurized vessel by use of a regenerative turbine or pump (Vendor: ECO2). For instance, if the efficiency of the pump pressurizing the feed to the gas transfer reactor is 80% efficient, and the energy recovery from the pressurized discharge is 80% efficient, then 64% of the energy can be recovered in this arrangement.

This pressurized arrangement allows pressurization with its associated high discharge D.O. concentrations, while consuming only approximately 500 kwhr/ton D.O. added and producing as much as 500 mg/L D.O. in the discharge.

It is possible to operate the cone at even higher pressures than in the water column by pumping through the system against a back pressure imposed by a throttling valve located on the discharge. Whenever water is pumped against an imposed back pressure the unit energy consumption will rise to about 1000 kwhr/ton D.O. This principle holds for pressures required to produce D.O. concentrations over the broad range of 100 to 500 mg/L. Thus if an increased unit energy consumption is acceptable, the tonnage of D.O. /day can be produced in a proportionately reduced size of oxygen transfer reactor. With proper design of the discharge diffuser it is possible to depressurize and dilute these very high D.O. concentrations without effervescent loss of D.O.

Table IV. Expected Results of a Speece Cone Installation at 50 ft Depth

A Speece Cone 12 feet in diameter and 15 ft tall placed 50 ft below the water surface will give the following results using a 45 HP pump:

- 60 mg/L discharge D.O.
- 34 cfs flow through cone
- 12,000 lb D.O. required per day
- >90% oxygen absorption
- 200 kwhr/ton D.O. consumed (if depth is 50 ft.)
- cost of units - $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.*

Pressurized Energy Recovery Oxygen Transfer System

This type of exceptionally high superoxygenated discharge has the advantage of requiring fewer supplemental oxygenation stations positioned at greater intervals.

The dissolved oxygen produced in the discharge of the Pressurized Energy Recovery System is proportional to the pressure under which the system operates. If the operating pressure is doubled, the dissolved oxygen concentration in the discharge would also be doubled along with a doubled energy requirement. Consequently the higher the pressure under which the system operates, the higher the dissolved oxygen in the discharge and the higher the energy consumption.

Thus exceptionally high dissolved oxygen concentrations can be produced by a recent proprietary system in pressurized vessels for 1000 kWh per ton of D. O. even at D.O. concentrations of 500 mg/L. Therefore if the D. O. in the discharge is kept below the spontaneous effervescence level, exceptionally high concentrations of D. O. can be produced with a unit energy consumption of approximately 1000 kWh per ton of D.O.

The only practical limit to this concept is the spontaneous effervescence level but this problem can be kept under control by proper dilution. The spontaneous effervescence level for pure oxygen dissolved in water is approximately 250% or 100 mg/L.

Turbine Mixers Operating In Confined Headspace – Emscher River Installation

The Emscher River in Germany has historically served as an open sewer because no prior treatment is applied to the municipal and industrial wastewaters which are all discharged into it. Subsequently the entire river is diverted through primary clarifiers and is then redirected into the river channel where it is completely diverted through an activated sludge treatment facility about 10 miles downstream from the primary clarification location. Ultimately a supplemental oxygenation system was installed on the Emscher River to raise the D.O. to approximately 10 mg/L so that it would remain oxic and thus odor free in this 10 mile stretch

The D.O. supplementation facility consists of a covered concrete tunnel through which the entire river flows. Submerged baffles at the beginning and end of this tunnel serve to provide a confined headspace above the water surface which is filled with an oxygen rich atmosphere into which the river water is splashed to accomplish oxygen transfer by means of surface aeration equipment suspended from the roof of the oxygenation tunnel. This system is similar to the principle of the old UNOX oxygen transfer process.

These systems can achieve high oxygen absorption efficiency with low unit energy consumption but are affected by dissolved nitrogen stripping. Target D.O. levels are limited to about 10 mg/L. Turbine mixers can scour basin bottoms if earthen. It should be noted, however, that these installations must be placed within the river channel to be effective.

Contained Atmosphere Surface Splashing

The original UNOX activated sludge process used pure oxygen and utilized a water sealed head space which was equipped with surface splashing turbines. One version utilized injection of the O2 down a hollow shaft below a submerged mixer as well as surface splashing turbines. Thus the water was splashed in contact with enriched O2 in the head space. The system operated at ambient pressure and was able to keep the O2 in contact with the water for an extended time. It could only operate with a D.O. in the water of less than 10 mg/L to insure an increased D.O. deficit. With a D.O. of less than 10 mg/L the unit energy consumption is below 1000 kwhr/ton of D.O. transferred. The entire reactor surface area is required for oxygen transfer, but achieves > 90% absorption affectively.

Sidestream Pressurized Oxygenation

Sidestream pressurization is a gas transfer technology which withdraws a relatively small sidestream of water, injects pure oxygen into the pressure side of the pump, and pumps it at high pressure through a long pipe loop. The water velocity is maintained sufficiently high enough to assure two-phase flow so that the gas/water interfacial area is quite high to maximize the rate of gas transfer. The system is pressurized to as much as 100 psig by a throttling valve on the discharge end which results in a C_{sat} concentration for pure O2 of 300 mg/L at 25 oC.

Depending on the diameter of the pipe loop, a velocity of at least 10 ft/sec is required to generate the turbulence required to maintain two phase flow. Since it requires nominally about 100 seconds of contact time between the O2 bubbles and the water regardless of the water pressure to achieve > 90% O2 absorption, the pipe loop must be about 1000 ft long. Since this is an excessively long pipe loop, it is common to make it shorter and thus sacrifice O2 absorption efficiency.

Criteria used to evaluate performance of this system involves: the oxygen absorption efficiency attainable, the unit energy consumed per ton of dissolved oxygen added, the dissolved oxygen concentration in the discharge, and the capital cost.

Sidestream systems are able to achieve very efficient oxygen absorption efficiency if the length and retention time within the pipe loop are sufficiently long (at least a hundred seconds). Operated at very high pressures, these systems can produce a highly superoxygenated discharge.

An advantage of such a system in Savannah Harbor would be that the system could be located along the edge of the shipping channel and discharge a highly superoxygenated effluent perpendicular to the harbor axis into the main channel. Disadvantages of the of the system are the high unit consumption required plus the limited oxygen absorption efficiency that is usually obtained if the length of the pipe loop and the residence time is not long enough to achieve very high oxygen absorption efficiencies.

To raise the rate of gas transfer, the gas/water interfacial area should be maximized and the D.O. deficit should also be optimized. Gas/water interfacial area is enhanced by increasing the amount of gas injected per unit volume of water and minimizing the resulting bubble diameter. The D.O. deficit is maximized by pressurizing the gas transfer system. The gas transfer equation is as follows:

$$dc/dt = K_l\,(A/V)(C_{sat} - C_{act})$$

Under these conditions of 100 psig pressurization, it is possible to achieve over 200 mg/L D.O. in the discharge. By proper design, most of this superoxygenated water can be retained in solution. Discharge at 50 ft below the surface and rapid dilution just after the pressure drop at the throttling valve would need to be incorporated. Rapid dilution can be achieved by directing all of this energy in the high velocity discharge into a shroud discharge tunnel which entrains bulk water containing low D.O., similar to that used with Venturi/jet gas transfer systems.

A sidestream pressurization unit capable of dissolving 40,000 lb D.O. per day would have the following design parameters:

- discharge D.O. : 200 mg/L
- flow of side stream ; 37 cfs (if 200 mg/L D.O. in the discharge)
- diameter of pipe constituting contact loop ; 26 inches
- cost of 1000 ft of 26 "diameter 316 SS ;__________________
- pump HP @ 70% efficiency ; 1380 HP (pumping against 100 psig)
- cost of pump ;____________
- unit energy consumption ; 1200 Kwhr/ton D.O.
- O2 absorption efficiency ; >90% (if pipe loop 1000 ft long)
- operating cost per ton D.O. ;___________(6 months/yr 6%, 15 yr)

Thus high levels of superoxygenation can be achieved, which proportionately reduce the fraction of a side stream required for a given tonnage of D.O. per day. As with all pressurized systems pumping against a throttling valve to achieve pressurization of the gas transfer reactor, the unit energy consumption rate is high, e.g. 1200 kwhr/ton D.O., which is a major drawback. Additionally the length/cost of the pipe loop are comparatively high so that less than 100 seconds detention time frequently results from the short lengths utilized in most cases.

U-Tube Oxygenation Technology

The U-tube aeration concept first applied in the Netherlands in 1958 exhibits excellent potential for dissolution of insoluble gas into a liquid. This process involves passage of a gas water mixture vertically down a shaft underneath the baffle and back up to the surface, providing prolonged contact of the bubbles with the water and pressurization of the bubbles by the hydrostatic head. Water is pumped down the center of this shaft to the bottom and then flows back through an annular space to the surface. A vertical shaft of considerable depth is required for this type of oxygen transfer technology.

Several reactions occur by injecting high purity oxygen into the downward flow: the contact of gaseous oxygen with the water will be in proportion to the depth and velocity characteristics of the system and since the water is flowing vertically downward or vertically upward, there will be no problem in maintaining two-phase flow of the oxygen bubbles and water if the velocity is sufficiently high. Also the head loss across the system will be relatively small due to friction loss (most of the head loss is related to the void volume differential of gas in the down leg and the up leg).

The oxygen absorption efficiency characteristic of a U-Tube oxygen transfer system will be related to the O2/water ratio that enters the system. Consequently at low O2/water injection ratios, higher absorption efficiency will be achieved, but lower discharge D.O. concentrations result. Conversely when the O2/water injection ratio is increased, the oxygen absorption efficiency will decrease but the discharge D.O. concentration will increase. It thus becomes obvious that higher oxygen absorption efficiency is realized at the expense of the D. O. concentration in the discharge.

Even though the depth of the U-tube is approximately 200 feet deep, oxygen absorption efficiency may not exceed 80 - 90% depending upon the water velocity through the system, the depth of the system, and the O2/water injection ratio realized. See Fig. __ for a schematic view of the system.

Advantages of U-Tube Technology

U-Tube oxygenation technology incorporates several desirable features when compared to other methods of raising D.O. levels. The major advantages of U-tube oxygenation are as follows:

- Oxygen transfer occurs in a pressurized reactor, which results in very high D.O. concentrations up to 50 mg/L at 28°C. A high rate of oxygen transfer per unit volume of reactor, up to 5400 mg/L per hour, may be achieved versus 100 mg/L per hour for conventional aeration tanks.
- Unit energy consumption per ton of D.O. is approximately only 400 kWh per ton, which is quite low because the head loss across the system is minimal, even though the oxygen transfer occurs at hydrostatic pressures of up to 175 feet.

- The oxygen bubble contact time is prolonged in transit through the U-Tube.
- Exceptionally high saturation concentrations are generated, enabling supersaturation of D.O. in the discharge.
- Oxygen gas bubble pressurization is accomplished hydrostatically, thus consuming low energy. Contrasted with the excessive energy consumption of pumped pressurization vessels which lose all of the input energy across the pressure throttling valve, no supersaturated D.O. may be lost by effervescence with pumped pressurization.
- No external pumping is necessary if the hydraulic head of the effluent is at least 5 feet above the harbor surface.
- Dissolved nitrogen stripping is minimized from the water as well as nitrogen gas dilution of the oxygen composition of the bubbles because gas transfer occurs in a pressurized vessel. Water saturated with nitrogen gas in air will strip if the nitrogen partial pressure in the gas phase is less than .79 atm. If the process is at atmospheric pressure, the nitrogen composition approaches 79%, but at 4 atmospheres the nitrogen composition approaches only 20%. This results in oxygen compositions of 21 % and 80% for 1 and 4 atm respectively.

The U-tube is comprised of a deep hole about 150 to 200 feet deep. The water flows down an open-ended pipe inside a casing and back up to the top through the annular space between the two pipes. See Fig___. The water velocity is approximately 6 to 10 fps, which greatly exceeds the 1 fps bubble rise velocity of the bubbles. Therefore when oxygen gas is introduced at the inlet, the bubbles are dragged along with the water flow down to the bottom and back to the top. Oxygen transfer is achieved by the hydrostatic pressurization, but also is enhanced by the turbulence and extended contact time. At 175 feet of hydrostatic head, the pressure is over 6 atm and with a 100% oxygen bubble, the saturation D.O. concentration is over 250 mg/L.

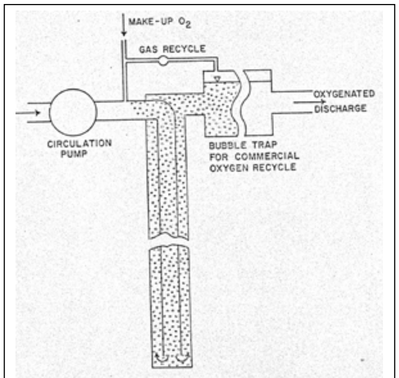


Fig. I U-TUBE OXYGENATION PROCESS SCHEMATIC

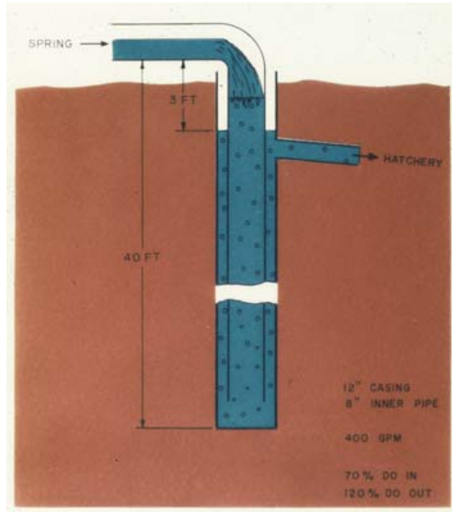


FIGURE 8. FISH HATCHERY OXYGENATION SYSTEM

Hydroflo

HydroFlo technology withdraws a sidestream of water into which high purity oxygen is injected, then directed through equipment in which the oxygen absorption takes place, and sent back into the harbor. Similar criteria are used to evaluate the HydroFlo technology performance as have already been mentioned: the oxygen absorption efficiency achieved, the unit energy consumption per ton of dissolved oxygen, the level of super oxygenated water present in the discharge, and the relative required spacing of units throughout the harbor.

HydroFlo units could be located on the edge of the shipping channel and discharge their high velocity superoxygenated stream back into the ship channel. However proprietary data needed to determine oxygen absorption efficiency which can be achieved by the HydroFlo technology is not available at this time.

Mobile Oxygenation Barge

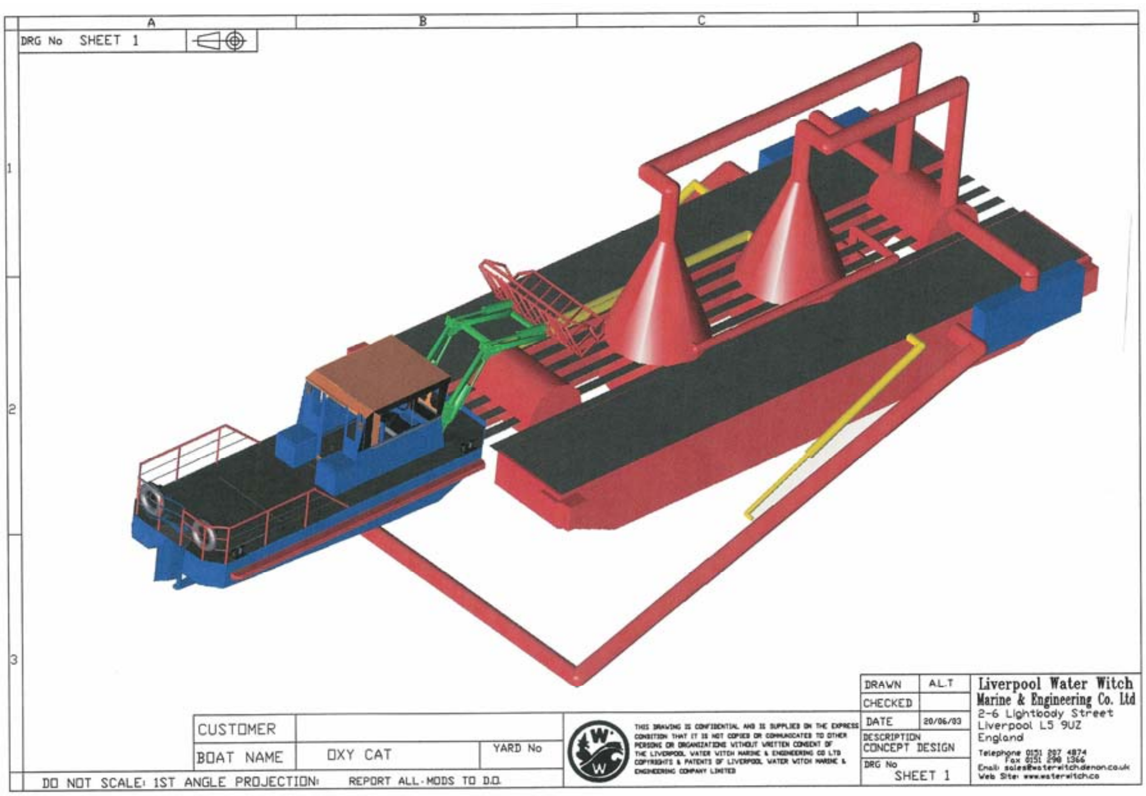
Mixing and transporting of the super oxygenated water within the harbor are key goals which must be achieved in a successful D.O. supplementation project. Oscillating tidal currents will be one of the main mechanisms which can be capitalized upon for movement of superoxygenated side streams away from 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.

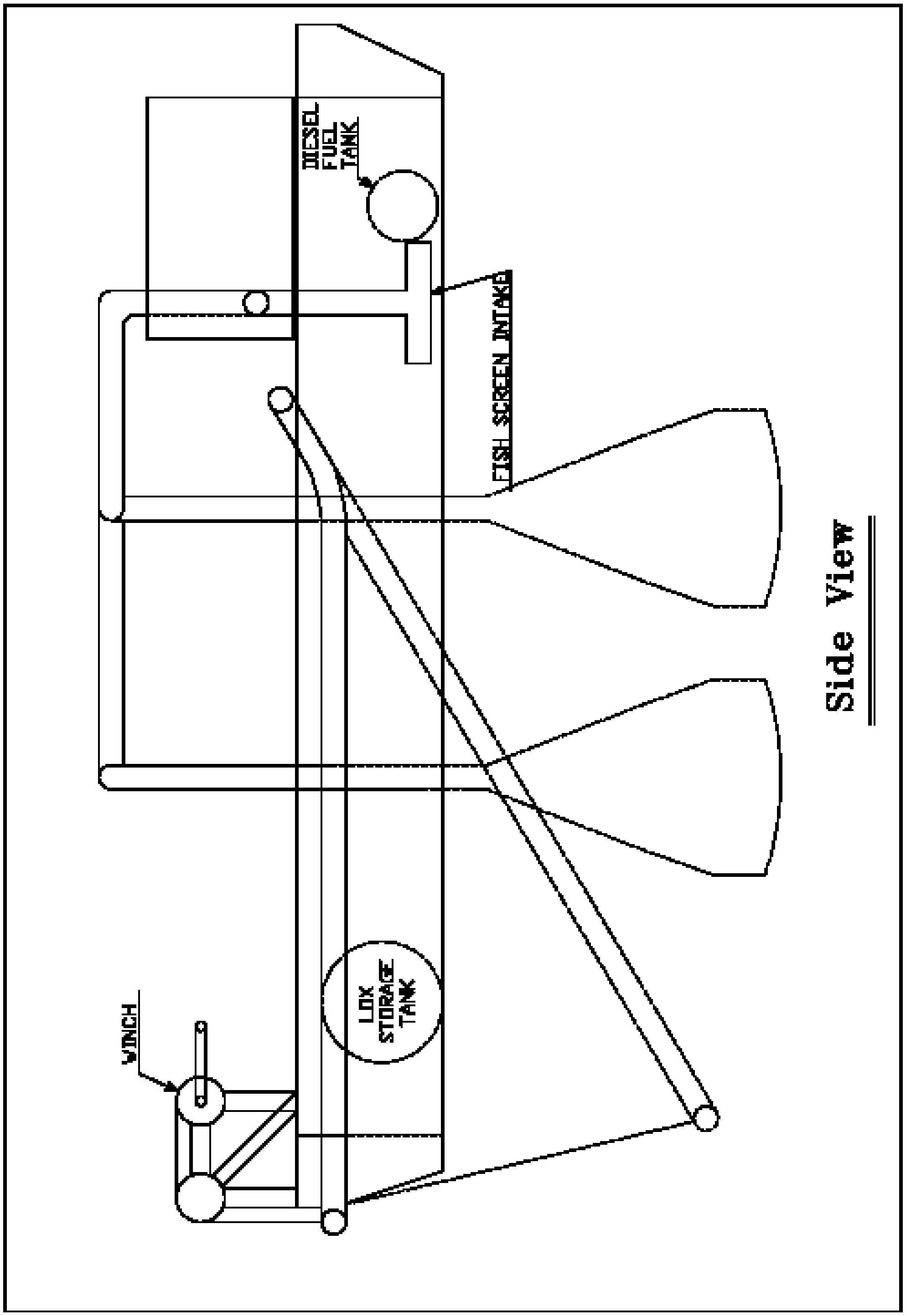
In such cases a logical solution would be to incorporate a means to deliver D.O. directly to the locations which are out of compliance. The concept of a self contained mobile oxygenation system could be used to address such deficiencies in tidal mixing effectiveness for effective transport of D.O. to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

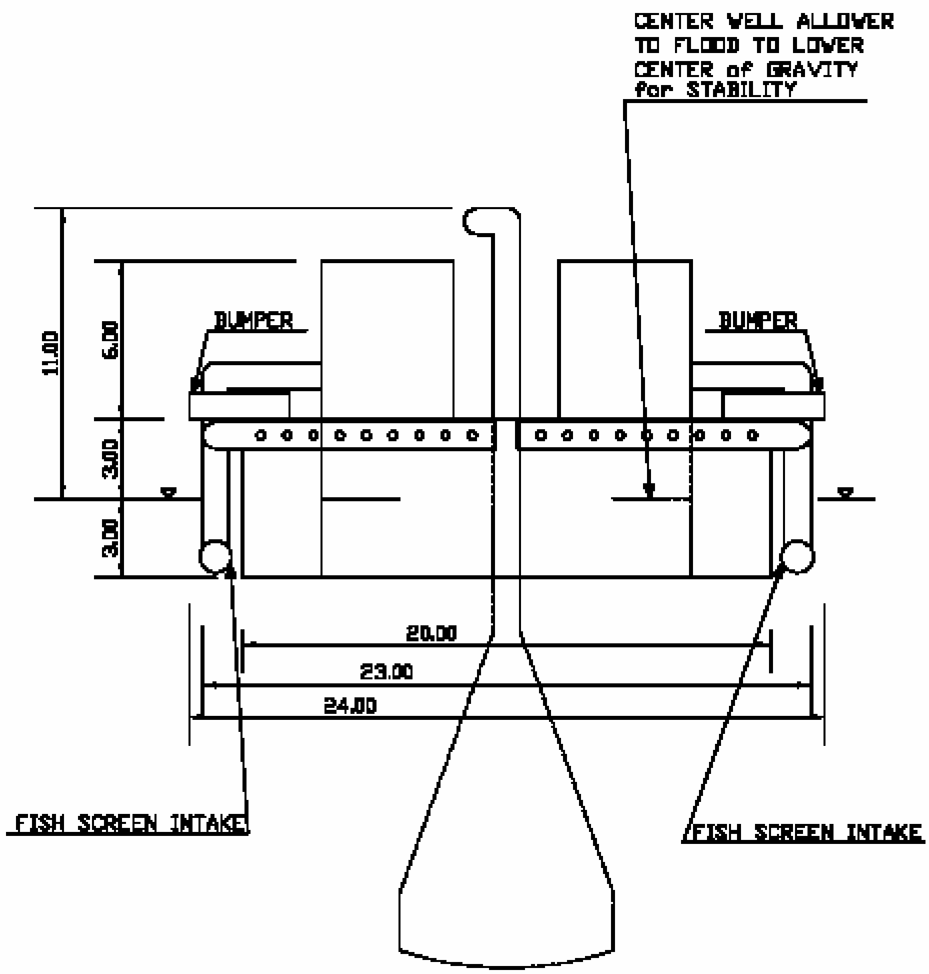
It would be advantageous to capitalize on the hydrostatic depth of the harbor for enhancement of oxygen transfer by placing the oxygen transfer reactor as far below the surface as possible. Of course there may be regions outside the main deep ship channel where the depths are much less deep that may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

The following Figs. __ 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 therefrom.





Side View


CENTER WELL ALLOWER
TO FLOOD TO LOWER
CENTER of GRAVITY
for STABILITY
BUMPER
BUMPER
11.00
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24.00
FISH SCREEN INTAKE
FISH SCREEN INTAKE

End View

IV. On-Site Performance Studies of Selected Superior Oxygenation Systems

A. Speece Cone Performance, Logan Martin Dam

This oxygenation system was designed to handle 21 ft.^{3} per second. The top diameter is 20 inches and the diameter at the bottom of the cone is 9 feet with a cone height of 15 feet and a bottom cylindrical skirt that was 5 feet high to contain the discharge piping. It was projected that the 21 ft.^{3} per second system could add 55 mg/L of D. O. if the inlet D. O. was 0 mg/L and the O2/water ratio injection ratio was 5%.

This proposed system would satisfy about one third full-scale D. O. requirements of 18,000 pounds of oxygen per day for a leakage flow of 700 ft.^{3} per second to raise the D. O. to 4 milligram per liter in the discharge from a background D. O. concentration of 1 mg/L in the influent. Therefore if this 21 ft.^{3} per second system was found to be successful it was decided that it would be combined in the final design with an additional system capable of handling another 42 ft.^{3} per second. This system was installed to determine its operational performance so that scale up problems for a full-size system would be minimized.

Oxygen/Water Ratio

The data are presented graphically showing O2/water ratio ratios of 3, 4, 5 and 6% respectively. The relevant points that can be drawn from the graphs are as follows.

Maximum oxygen absorption efficiency occurred at a water flow rate of 22 to 25 ft.^{3} per second through the system. A slight reduction in absorption efficiency occurred below this range and a more rapid decline occurred at higher velocities.

All oxygen absorption efficiency decreased with increasing O2/water ratios. Likewise all oxygen absorption efficiencies declined with increasing water flow rate in excess of 22 to 25 ft.^{3} per second.

The greatest D. O. increase resulted at water flows of 22 to 25 ft.^{3} per second for all oxygen water ratios, as mentioned previously, because increased water flow resulted in bubbles being swept out of the system prematurely. Thus oxygen absorption efficiency was thereby reduced, as reflected in the lower D. O. concentration in the oxygenation system discharge.

The pressure losses across the system are plotted in Fig. __. Pressure at the oxygenation discharge with no flow-through the system was 52 feet, reflecting the static head of water above the dam with respect to the location of the oxygenation cone. With no oxygen in the injection, the discharge pressure was 44 and 42 feet at water flows of 22 and 25 ft.^{3} per second, respectively and at an O2/water injection rate of 4%. Discharge pressures were 38 and 37 foot. It is to be noted that the total head loss across the oxygenation cone was nearly constant at 6.2 feet regardless of water flow through the system when oxygen was injected at 4% O2/water ratio.

Results

The oxygenation cone has a volume of 320 ft.³. The five foot-high cylindrical section on the bottom of the cone that contains the discharge piping also had a volume of 320 ft.³, resulting in a total volume of 640 ft.³. At the design flow of 22 ft.³ per second and 4% O2/water ratio, the system added 48 mg/L of D. O. to a background influent D. O. of 3.6 mg/L for a total of 5600 pounds of D. O. per day. This is equivalent to 9 pounds of D. O. per cubic foot per day or 100 mg/L per minute of D. O. at 90% oxygen absorption efficiency. The average pressure in the cone was approximately 29 feet at the centerline of the cone and the water temperature was 86°F. At this pressure and temperature the saturation D. O. would be 66 mg/L, if the gas phase was 100% oxygen. The discharge D. O. was 51 mg/L and the oxygen content of the bubbles within the oxygenation cone was approximately 83%, as measured with a 4% O2/water injection rate, indicating the oxygenation system was able to achieve 94% of theoretical saturation under these conditions. This is indicative of a very good oxygen transfer system since the hydraulic retention time is only about 30 seconds.

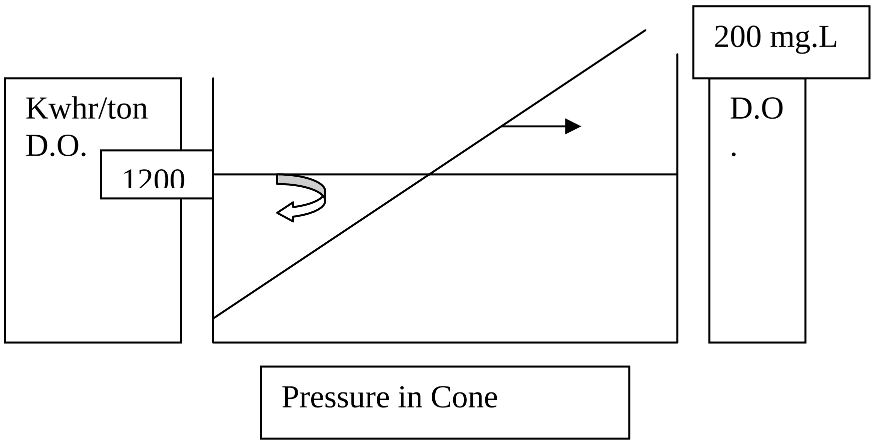
In the flow range of 22 to 25 ft.³ per second with an O2/water injection ratio of 3%, the discharge D. O. was 42 mg/L for a net increase of 38 mg/L over background. Under these conditions the absorption efficiency was 95%. When the O2/water injection ratio was increased to 4% under the same water flow conditions, the discharge D. O. was 51 mg/L over the background concentration of 4 mg/L, resulting in an oxygen absorption efficiency of 87%.

Pressurized oxygen transfer

The nature of pressurized oxygen transfer is demonstrated by the fact that when pressurization was incorporated it increased the unit energy consumption rate to about 1200 kWh per ton of D.O. In cases where no pressurization was utilized, such as placing the oxygen transfer device on the bottom of the ship channel 50 foot below the surface, a discharge from a Speece Cone would be about 60 mg per liter of dissolved oxygen. A 12 foot diameter cone can handle 35 ft.³ per second of water flow. The head loss across the cone is approximately 10 feet, which would thus require a 55 hp pump, if it were operating at 70% efficiency. Thus each cone could deliver approximate by 11,000 pounds of dissolved oxygen per day and the unit energy consumption would be approximately 200 kWh per ton of dissolved oxygen added.

If the Speece Cone were operated at a pressure of 215 feet of head it would produce a discharge dissolved oxygen level of 200 mg per liter and a 12 foot diameter cone would be able to deliver 38,000 pounds of dissolved oxygen per day. To pump 35 ft.³ per second against a head of 215 foot of head plus 8 foot of head loss would require a

1300 hp pump. The unit energy consumption would be approximately 1200 kWh per ton of dissolved oxygen.



These data suggest that a Speece Cone operating under ambient pressure at the bottom of the Savannah Harbor Ship Channel would produce 60 mg/L in the discharge and be able to deliver 11,000 pounds of dissolved oxygen per day with a unit energy consumption of less than 200 kWh per ton of D.O. If the cone was operating at 215 ft of pressure it would produce 200 mg/L D.O. in the discharge and deliver 38,000 pounds of oxygen per day, with a unit energy consumption of 1200 kWh per time of dissolved oxygen.

Life cycle costs of non-pressurized, pressurized, and energy recovery oxygen transfer

Since the above systems achieve greater than 90% oxygen absorption efficiency, whether operated under ambient or pressurized conditions, the key comparison is life cycle cost of energy consumption and additional oxygen transfer volume. The non-pressurized system would require approximately 3 1/2 times as many Speece Cones as would the pressurized system. Therefore the reduction in energy costs must be compared with the increase in capital cost for additional cones.

Assuming 50% utilization of the system throughout the year, the following life cycle costs result for transfer of 38,000 lb D.O. per day.

Assume equivalent power costs for diesel engines to be $0.12/kwhr. Power for non-pressurized system would consume 19 T/d x 200 kwhr/T = 3800 kwhr/day x $0.12/kwh x 180 d/y x PWF of 9.7 (6%@ 15 yr) = $800,000 for the present worth. The equivalent cost for the pressurized system would be 6 times this or $4,800,000. This is considerably more that the cost for an additional 2.5 Speece Cones of 12 ft diameter needed to transfer 38,000 lb D.O./day. Thus it appears that the non-pressurized mode of supplementing D.O. is economically more favorable than the pressurized mode.