Protecting Our Water Environment

Metropolitan Water Reclamation District of Greater Chicago

RESEARCH AND DEVELOPMENT DEPARTMENT

REPORT NO. 01-2

LITERATURE SEARCH OF POSSIBLE AERATION SYSTEMS AND WASHDOWN PROCEDURES FOR USE WITH THE PROPOSED McCOOK RESERVOIR

PART I

COMPARISON OF U-TUBE, CRYOGENIC OXYGEN, AND DIFFUSED AIR TECHNOLOGY ALTERNATIVES FOR AERATION OF DEEP RESERVOIRS AND RESERVOIRS WITH LARGE DEPTH VARIATIONS – A LITERATURE SEARCH AND REVIEW

February 2001

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By

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ABSTRACT

This paper is the result of examining the scientific literature for useful information concerning the following three separate aeration systems which could be used to aerate the McCook reservoir or a similar deep reservoir.

1. Pure oxygen aeration.
2. U-tube aeration.
3. Conventional aeration using compressed air.

Aeration of deep reservoirs and impoundments is an accepted technology for providing dissolved oxygen to deep waters in reservoirs. The above three techniques are available to accomplish this objective.

Based upon a review of 2,100 titles and/or abstracts, approximately 100 articles, books, or journal proceedings were obtained for detailed study. The following may be concluded from the literature search:

1. No information was found which is directly applicable to the design of the McCook Reservoir aeration system. This is due to the unique design constraints of the McCook Reservoir, namely, its varying water depth, its varying BOD_5 loading, and the need to maintain adequate

dissolved oxygen concentrations in the upper as well as lower layers of the water column.

2. Also, the literature review did not provide any information which would conclusively eliminate any of the above three aeration systems from further consideration.

Thus, further experimental and/or theoretical work may be required in order to design the McCook Reservoir aeration system.

ACKNOWLEDGMENTS

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DISCLAIMER

The mention of proprietary equipment and chemicals in this report does not constitute endorsement by the author.

INTRODUCTION

The McCook Reservoir site is located on Metropolitan Water Reclamation District of Greater Chicago (District) property in southwestern Cook County, Illinois. The McCook Reservoir, as proposed, will be a surface reservoir which will provide for storage of combined sewage overflows from the north, central and west portions of the District. This storage will reduce flood damage and minimize releases of untreated combined sewage to the waterways within and/or affected by the District. The Mainstream and Des Plaines tunnel systems were constructed and are operated by the District. These tunnels will transport combined sewage to the McCook Reservoir when flows exceed the pumping capacity of the Stickney Water Reclamation Plant (WRP). The McCook Reservoir, as proposed, will be composed of a 300 acre-feet (97.75 million gallons) sump, and two 10,700 acre-feet (3.49 billion gallons) stages for a total of 21,700 acre-feet (7.1 billion gallons). The proposed reservoir would be excavated in the bedrock immediately underlying the Chicago area.

The rock formation immediately underlying the Chicago region is primarily Silurian Dolomite, (dolomite = $CaMg(CO_3)_2$) part of a deposit greater than 400 million years old. The rock is part of the Niagaran series that extends under much of the midwest and northeast and is the same formation forming the lip of Niagara Falls in New York State and Canada (Bretz, 1939). The stone is more specifically part of the Racine (upper) formation of the Niagaran series (Willman, 1971). The dolomite is, in some areas, 500 feet thick (Willman, 1973).

An aeration system consisting of coarse bubble diffusers using either air or pure oxygen and/or U-tubes using either air or pure oxygen will be used to reduce the possibility of anaerobic conditions developing in the reservoir, and prevent stratification of the reservoir. Because each filling event is unique, the aeration system must be able to provide air under a variety of water depths to a maximum of 270 feet (Sorn, 1998). This report will examine using air or pure oxygen and/or U-tubes using either air or pure oxygen to reduce the possibility of anaerobic conditions developing in the McCook Reservoir.

Setting

The McCook Reservoir will be excavated in southwest Cook County in Silurian Dolomite for the purpose of storing combined sewer overflows (CSOs) as part of the Tunnel and Reservoir Plan (TARP). Nearby Du Page County is considering use of old quarries in Silurian Dolomite as temporary reservoirs for flood control (Charlton, 1994). TARP Phase I includes structures which will enhance water quality in the Chicago area and includes about 110 miles of tunnels, collector and drop shaft systems which connect local sewers to tunnels, and upgraded treatment works. Phase II involves the structures which are primarily involved with flood control and flood damage reduction (Price and Tillman, 1991). An earlier proposal (Buschbach and Helm, 1972) examined a proposal to tunnel through the Silurian Dolomite to formations as deep as 800 feet below surface levels. The current plan includes use of a reservoir for temporary storage for combined sewer and storm flow (Fletcher, 1991). A hydraulic analysis of the proposed McCook Outlet Manifold was presented by Stockstill (1993). The storage system would be sufficient to capture the runoff from a 30-year, 24-hour runoff. The water surface elevation would always be below the surface elevation. The McCook Reservoir is expected to eliminate or severely restrict approximately 10-15 combined sewer overflow events per year. Water could be stored for as long as 70 days in the reservoir. A variety of research and design activities are being performed to support the aeration system design for the reservoir (Sorn, 1998).

Reservoir Aeration System: Definition of the Aeration Problem

Currently it is projected, based on 1995 to 1997 data, that stormwater and CSO to the McCook Reservoir could have a BOD_5 of approximately 50 mg/L with a range of 10 to 174 mg/L and a median of 37 mg/L (Zhang et al., 2000). As much as 250 million gallons per day (MGD) of overflows could be pumped back from the McCook Reservoir to the Stickney WRP for treatment. With the 7.1 billion gallon reservoir, and multiple storms, stormwater and CSO could be stored for as long as 70 days. Such a system has the potential to become septic within a day. A BOD_5 of 50 milligrams per liter is equivalent to an ultimate demand of 73.5 milligrams per liter where k = 0.1 (base 10). A total oxygen requirement for the system to prevent septicity the first day would be $73.5*(1-10^{-kt})$ mg/l = 15 mg/l (where k = 0.1 (base 10) and t = 1). This is equivalent to a total of 15 mg/l*8.34lbs/MG/mg/l*7,000 MG = 875,700 lbs (438 tons) of oxygen on day one. Another way of expressing this is 875,700 lbs /24 = 36,488 lbs oxygen per hour or 438 tons/24 = 18.25 tons of oxygen per hour. There is need to determine the most efficient way of fulfilling the aeration requirement in a reservoir with varying depth.

Study Objectives and Scope

This paper is the result of examining the scientific literature for useful information concerning the following three separate aeration systems which could be used to aerate the McCook reservoir or a similar deep reservoir.

1. Pure oxygen aeration.
2. U-tube aeration.
3. Conventional aeration using compressed air.

The District has experience only with fine bubble aeration using porous ceramic diffusers at its seven WRPs, and these diffusers are used at a depth of 15 feet. Two instream aeration stations were constructed in 1979 and 1980 at Devon Avenue on the North Shore Channel and at Webster Avenue on the North Branch Chicago River. They use compressed air, distributed via bottom diffusers, to transfer oxygen to the water column during periods of low dissolved oxygen (Butts, 1988). The District has constructed five sidestream elevated pool aeration (SEPA) stations on the Calumet Waterway System (CWS) for replenishing DO on the waterway (Farnan, 1998).

Where relevant, aeration information concerning activated sludge or aerated lagoons, and lake waters containing low BOD_5 were included in the literature search but the emphasis of the literature survey was placed on aeration of deep reservoirs with high BOD_5. The survey included not only the performance of aeration systems but also:

1. Economics,
2. Reliability, and
3. Safety.

MATERIALS AND METHODS

Forty-two databases were examined at the Galvin Library at the Illinois Institute of Technology (Chicago, Illinois), Crerar Library at the University of Chicago (Chicago, Illinois), or on-line on the Internet. Only one database, the Illinois State Geological Survey, was a hard copy. All data bases are listed in Table 1. Key words used in searching the databases are shown in Table 2. These databases yielded approximately 2,100 possibly relevant scientific texts which were examined by title and abstract, if available.

Based upon a review of these 2,100 titles and/or abstracts, approximately 100 articles, books, or journal proceedings were obtained and copied. These texts were reviewed and represent the basis for the literature review contained in this report.

TABLE 1

DATABASES USED TO SEARCH FOR DEEP AERATION ALTERNATIVES

COMPLETED AT ILLINOIS INSTITUTE OF TECHNOLOGY

Database	Description
Academic Press	Journals
Bowkers Books in Print	Books published in the U.S.
Carl Uncover	17,000 Multidisciplinary Journals
ASCE Engineering Database	Civil Engineering
Current Contents	Research Journals (1990-present)
Elsivier	Engineering and Science Journals
U.S. Govt. Printers Office	Government Documents
IIEE	Electrical Engineering
Newspaper Abstracts	25 Newspapers
OCLC Contents First	Journal Abstracts (12,500 Journals)
OCLC Papers First	Tables of Contents
OCLC Proceedings First	Index of Conference Proceedings
Pollution Abstracts	Environmental Engineering

TABLE 1 (Continued)

DATABASES USED TO SEARCH FOR DEEP AERATION ALTERNATIVES

ILLINOIS STATE GEOLOGICAL SURVEY

Database	Description
Illinois State Geological Survey	Hard Copy Catalogue

PERFORMED ON INTERNET

Database	Description
WEF	WEF Journals
EPRI	Electrical Power Research Institute
LEPAC	Army Corps of Engineers

PERFORMED BY CRERAR LIBRARY

Database	Description
BIOSIS	Previews 1969-present
NTIS	National Technical Information Service
Compendex	
Oceanic Abstracts	
Meteorological and Geophysical Abstracts	
SciSearch	Cited References 1990-present
ASFA	Aquatic Sciences and Fisheries
CAB	

TABLE 1 (Continued)

DATABASES USED TO SEARCH FOR DEEP AERATION ALTERNATIVES

PERFORMED BY CRERAR LIBRARY (Continued)

Database	Description
GeoArchive	
Inside Conferences	
GeoRef	
JICST	Japanese Science and Technology
Fluidex	Fluid Engineering Abstracts
Wilson	Applied Science and Technology Abstracts
Water Resources Abstracts	
WATERNET	
GEOBASE	
SciSearch	Cited References Science database 1974-1989
Enviroline	
Environmental Bibliography	
EMBASE	
TOXLINE	
ANTE	New Technology and Engineering
APILIT	

TABLE 2

KEY WORDS USED TO SEARCH DEEP AERATION ALTERNATIVES

KEY WORDS USED SEARCHING DATABASES AT THE ILLINOIS INSTITUTE OF TECHNOLOGY

U-tube	cryogenic oxygen	pure oxygen	aeration
reservoir	McCook	Thornton	dolomite
Federal Quarry	liquid oxygen	stormwater	EPRI
TVA	reservoir aeration	oxygen transfer	Silurian
Niagaran	oxygenation	Speece	Boyle
Redmon	Army Corps Engineers	oxygenation	energy
releases	dissolved oxygen	washdown	diffuser
hypolimnetic	diffused	nuisance	dam
karst	fine bubble	coarse bubble	odor[1]
hydrosuction[1]	dredging[1]	disinfection[1]	

KEY WORDS USED TO SEARCH ILLINOIS STATE GEOLOGICAL DATABASE ARMY CORPS OF ENGINEERS (LEPAC) AND WEF DATABASE

hydraulic	improvement	accident	options
comparison	feasability	improvement	quarry

KEY WORDS USED BY THE CRERAR LIBRARY FOR SEARCHING DATA BASES

reservoir	water	deep	u-tube
cryogenic	pure	oxygen	aeration

KEY WORDS USED TO SEARCH ELECTRICAL POWER RESEARCH INSTITUTE DATABASE

reservoir	aeration

[1]Words used only in association with another key word.

BASIC CONCEPTS

Biochemical Oxygen Demand

Biochemical Oxygen Demand (BOD) is defined as the amount of oxygen required by bacteria while stabilizing decomposable organic matter under a clearly defined set of conditions (American Public Health Association, 1995). The standard BOD calculation allows calculation of BOD for any time period.

DO

Oxygen is sparingly dissolved in water. Under atmospheric conditions approximately 9.0 mg/l represents the saturation value of oxygen in water. Henry's Law may be used to calculate the amount of oxygen present at saturated conditions. The low solubility of oxygen is an important factor that limits self-cleaning capacities of streams and lakes and is one of the major reasons for treatment plant construction and operation. Recreational and water supply uses are often a function of DO concentration. In the absence of DO, sulfate in water is reduced to hydrogen sulfide which is often the most prevalent odorous compound in wastewater (ASCE/WEF, 1995).

Methods for measurement of oxygen transfer efficiency were the subject of a joint United States Environmental Protection Agency (USEPA)/American Society of Civil Engineers

(ASCE) conference (1978). Ultimately a standard for measuring oxygen transfer efficiency in water was published by ASCE (1992).

Increasing the DO Content of Water

There are a large number of methods used for increasing DO concentrations in wastewater (Boyle, 1986) (Water Pollution Control Federation, 1977). Where relatively low concentrations of oxygen are required at low transfer rates, natural reaeration or addition of small amounts of air may suffice. Most studies that generated information on reservoir aeration concern systems, other than CSO reservoirs, cannot be directly related to the McCook Reservoir. This literature survey examines two newer methods for increasing oxygen concentrations in water, pure oxygen and U-tube and compares them to more conventional methods.

PURE OXYGEN SYSTEMS

The District has considered a diffuser system using pure oxygen for the McCook Reservoir (Macaitis, 1990). Cryogenic oxygen would be the main oxygen supply system, supplying as much as 765 tons of oxygen of a total of 897 tons per day under maximum oxygen requiring conditions estimated at that time. Since then, the amount of oxygen required has been lowered to 438 tons maximum. Pure oxygen systems are used in sewer systems for the oxidation of sulfide products in sewers or force mains (Speece et. al, 1990).

Commercial oxygen may be dissolved in water for as little as $6.50 per ton and becomes economically attractive when used for process stability. (Speece et al., 1990). For conventional diffused aeration with cryogenic oxygen, there should be an enclosed air space, e.g., a cover, or enough depth to minimize the interchange area/volume ratio and to avoid excessive losses of oxygen to the atmosphere.

Oxygen may be generated on-site or liquid oxygen may be transported to the site.

Pure oxygen systems offer the following advantages:

1. Henry's Law states that the saturation concentration of a gas in liquid is directly proportional to the partial pressure of the gas in the

atmosphere in contact with the liquid. For pure oxygen in water at 0 degrees Centigrade the Henry's Law constant for water at one atmosphere is 70.5 mg/l. (ASCE, 1987). High purity oxygen where the proportion of oxygen is near 100 percent increases the equilibrium saturation concentration by a factor of 4.7.

2. There may be a reduction in the power required for the aeration system.
3. There may be a reduction of periods of zero DO concentration.
4. Elimination of need for blowers.
5. May allow increased capacity during periods of organic overload.

The ASCE (1983) published an extensive document comparing air and pure oxygen systems for the activated sludge process. The document included a review of oxygen activated sludge system data from full-scale systems in operation. Also included was a general discussion of the various types of systems available, operational characteristics, substrate utilization rate, sludge yield, and liquid-solid separation. Some general design considerations were included for the design of oxygen activated sludge systems.

A difficulty noted in this document was the challenge of comparing conventional air systems economically with pure or enhanced (periodic or continuous addition of oxygen to conventional air aeration) oxygen systems. However, such large pure oxygen activated sludge systems have been installed at Detroit (900 MGD), New Orleans (122 MGD), Louisville (105 MGD), and Denver (72 MGD).

The District, as mentioned earlier (Macaitis, 1990), has prepared a report discussing a barge system for adding cryogenic oxygen to the McCook Reservoir. Maximum deoxygenating loads for the reservoir at that time (1990) were estimated to be on the order of 900 tons per day. A barge system with a trailing diffuser boom was determined to be the most efficient method to add cryogenic oxygen. Macaitis recommended that the cryogenic oxygen barge system with oxygen at $55 per ton should be considered as a cost effective method of delivering oxygen to the reservoir.

Systems for injecting pure oxygen through diffusers have been utilized at a number of deep water lakes. In general, few of these contain water with a BOD_5 exceeding 5 mg/L and do not require oxygen addition on a daily basis other than that supplied by moderate mixing, but need intermittant additions of oxygen. Several of these systems will also be discussed in a latter section of the report dealing with U-tubes. An aeration demonstration project at J. Strom Thurmond Dam and Reservoir (Mauldin et al., 1988) using pure oxygen diffusers was performed to determine the feasibility of using pure oxygen diffusers to maintain a relatively high (6 mg/l) DO in a fishery downstream of the proposed Richard B. Russel Dam. The system used fine bubble diffusers. The fine bubble diffusers yielded a 78-85 percent oxygen transfer during the first 100 feet of water above the diffusers. As many as 90 tons of oxygen were added per day. Gas analysis indicated that the small bubbles (undefined as to size) averaged over 80 percent transfer efficiency while large bubble diffusion (again undefined) resulted in less than 50 percent efficiency. Oxygen costs were given as $43 to $86 per ton.

The Tennessee Valley Authority (TVA) (Hajerioua et al., 1995) evaluated procedures to optimize the location and predict the aeration efficiency of oxygen diffusers in the Cherokee Reservoir. This system was designed to add 2 mg/l to the reservoir at an 80 percent oxygen transfer rate. It was found that a total of 5000 tons of oxygen can be added per year at approximately $125 per ton. Overall the TVA adds DO to river systems, so this information may not be directly applicable to the McCook Reservoir. Overall this is a problem with most studies of dams.

Speece et al. (1982) evaluated the use of pure oxygen at the Clark Hill Dam near Augusta, Georgia. He found that the cost of on-site production of cryogenic oxygen was $30 per ton. Oxygen transfer efficiency was given as 85 percent.

Speece et al. (1990) evaluated the use of commercial oxygen use in water quality management. They addressed two specific uses,

1. Cost per pound of oxygen, and
2. Water quality objectives which may not be met economically using air (such as near oxygen saturation conditions) but would be economically feasible using oxygen.

Most potential projects for the use of high-purity oxygen require elevated DO concentrations and/or low levels of agitation where aeration with air is usually less economical than aeration with pure oxygen. Examples of successful pure oxygen use are gravity sewers, force mains, primary clarifiers and activated sludge operations where volatile organic compound (VOC) emission requirements restrict agitation, prevention of sludge bulking in activated sludge, preventing excessive slime buildup on rotating biological contactors, minimizing agitation in fluidized bed biological reactors, DO maintenance in river, canal, and lake management, and hydropower or dam discharge oxygenation. Methods of dissolution include conventional diffuser systems, downflow bubble contactors, U-tube contactors (to be discussed in a later section), and countercurrent packed column contactors. The cost of various delivery systems for pure oxygen is given in a table which will be discussed more fully in a later section. Colt et al. (1993) investigated the use of pure oxygen as part of a plan to double the size of salmon runs in the Columbia River basin. They used Michigan Type Pure oxygen columns. These differ from normal diffusers and are described as follows:

1. There is no medium within the column.
2. The diameter of the discharge pipe from the column is smaller than the column diameter.
3. The transfer system produces a vacuum within the column.

Transfer efficiencies of 30 percent to 60 percent were achieved in columns less than two meters in length.

The effects of hypolimnion pure oxygen aeration were examined at the Clark Hill Dam on the Savanna River in Georgia and South Carolina (Dudley and Quintrell, no date). Due to relatively healthy fish populations before the aeration, it was difficult to see any significant differences afterward.

An anonymous article in Chemical Engineering News (1973) described pure oxygenating systems (Union Carbide) for lake aeration without dissolving excess nitrogen into the water. A bottom circulating system was utilized which withdrew water from the hypolimnion, injected the water with pure oxygen and returned the oxygen saturated water to the hypolimnion. This system keeps the hypolimnion water cold and prevents the hypolimnion from becoming destratified and thus allows the reservoir to support cold water fish.

Speece (1994) found that the addition of pure oxygen through diffusers was an efficient way to increase oxygen without causing destratification of lakes. This is because a small sidestream can be oxygenated to a relatively high oxygen concentration (130 mg/l) and returned to the hypolimnion.

Weinzapfel et al., (1996) discussed recent developments and synergies in the use of oxygen for biological treatment of wastewaters from the pulp and paper industry in France. More stringent standards in the paper industry and cost competitiveness because of new technologies have led to an increased use of pure oxygen in the treatment of wastewaters in the pulp and paper industries. Land availability is also a concern in Europe and pure oxygen systems require 50 percent to 75 percent less land than conventional aeration. Comparison of the economics of high pressure to liquid state storage of oxygen is also a consideration. The primary costs to be compared are storage vessel construction, transportation, power to achieve storage state and product loss. Special piping must be used for cryogenic operations (Nayyar, 1992). This piping must meet the structural demands imposed by low temperatures. Thermal efficiency of the piping system is critical since heat addition to the system will result in loss of product concentration.

Improper handling of cryogenic or high pressure gases can cause serious accidents (Woodward, et al., 1994). The design and safety features of modern containers render the possibility of catastrophic failure miniscule. Accidents with cryogenic and compressed gases are almost always the result of human error.

Problems Associated with Available Pure Oxygen Aeration Studies

1. For aeration systems using coarse bubble diffusers, investigations conducted over relatively shallow depths demonstrated increased oxygen transfer efficiency (OTE) as depth increased (ASCE, 1987). Price and Tillman (1991) performed a compilation of studies performed by a variety of investigators. They concluded that OTE using coarse diffusers could be estimated by a conservative linear regression using the worst case transfer for each depth:

$$OTE\ (\%) = 0.6067z$$

where z = depth of diffuser in feet. Thus for a reservoir depth of 150 feet the OTE would be 0.6067*150 = 91%. Most of the DO, however, would be transferred into the lower portion of the reservoir, not into the upper levels which would be in contact with the atmosphere.

2. A portion of the increased transfer efficiency seen at increased depths is a result of increased pressure. An additional atmosphere of pressure is added every 34 feet of diffuser depth under water.

3. It appears likely that the bulk of the oxygen transfer in deep reservoirs takes place near the bottom of the reservoir due to the increased pressure.

4. This is exactly what is required in most impoundments as the hypolimnion is where oxygen depletion takes place and thus where the oxygen must be replaced.

5. There would be little mixing during the addition of pure oxygen during oxygen aeration.

6. In the absence of data of oxygen concentration at various depths, it would be necessary to perform deep aeration studies to assure that sufficient oxygen reached the upper layer of the reservoir.

U-TUBE

U-tube aeration consists of a shaft from 10 meters to >100 meters in length that is divided into two zones, a downward flow zone (downcomer) and an upward flow zone (upcomer). Air or pure oxygen is added to the influent water in the entrance of the downcomer, the mixture travels to the bottom of the downcomer tube and then back to the surface through the upcomer tube. The downward velocity of the water exceeds the buoyant velocity of the bubbles which are swept down through the downcomer, underneath a baffle and back to the surface through the upcomer. The gas-liquid mixture undergoes a temporary pressurization produced by hydrostatic head, resulting in greater oxygen transfer. Bruijin and Tuinzaad (1958) found that aeration efficiency was related to greater U-tube depth.

Some advantages of the U-tube are:

1. The hydrostatic head pressurizes the bubbles and increases the dissolved oxygen deficit by increasing the saturation concentration.
2. The buoyant force of the bubble causes turbulence at the bubble surface which results in a high rate of surface renewal, increasing the transfer rate.

3. Power requirements for air injection are low because air or oxygen is injected at shallow depths within the U-tube (Speece et al., 1969).

The transfer economy and capital costs for U-tube operations for these applications appear to be competitive with conventional aeration systems. Effervescence can be a problem if the supersaturated U-tube effluent is exposed to the atmosphere (Speece et al., 1969).

The USEPA performed an evaluation of U-tubes primarily with air aeration systems (Mitchell, 1973). The evaluation concluded that U-tube aeration was found to be a practical, flexible and efficient aeration method for a number of applications. While U-tubes do not appear to be competitive in activated sludge systems, in systems where it is required to increase DO concentrations to near saturation, the U-tube has an advantage. U-tube systems can be designed with no moving parts, require little maintenance and no operating labor. These advantages can result in substantial cost savings over other aeration methods. It was further concluded that a satisfactory basis of designing U-tubes existed in 1973. Full-scale systems had been designed, constructed and operated in sanitary sewer systems in Louisiana and Texas. The USEPA report also recommended that U-tubes be used for any application which required the raising of the DO level of a flowing water or wastewater stream. The USEPA at that time (1973) indicated that more consideration should be given to the use of pure oxygen with U-tubes.

Speece et al., (1980) performed an extensive study of various sizes of U-tubes for variations of velocity, depth, oxygen/water ratios and air/water ratios. It was found that commercial oxygen could be absorbed for as little as $6.50 per ton. The study indicated that the optimum design for minimal costs would be a U-tube of 25 to 60 meter depth and a velocity of 1.8 to 3.0 meters per second. DO levels as high 95 mg/l were recorded in a 61-meter deep U-tube. The study also indicated that the DO did not come out of solution at the upper levels of the upcomer.

Speece (1995) also reported a study at the Tombigbee River in Alabama where DO levels in a receiving stream restricted operation of two papermills. One U-tube added 12,000 lbs. of oxygen per day and the other added 40,000 lbs. of oxygen per day. The author concluded that for DO increases of greater than 4 to 5 mg/l, pure oxygen can be a more economical source of oxygen addition than conventional aeration. For a river system, pure oxygen combined with U-tube aeration also has the advantage of avoidance of supersaturation of nitrogen gas which can affect local fisheries. The use of pure oxygen resulted in oxygen absorption efficiency as high as 80 percent to 90 percent and was approximately 0.10 kWhr per kilogram of oxygen dissolved. Head loss across a 175 foot deep U-tube was 5 feet (1.5 meters). High DO water was discharged through the diffuser system at the river bottom. Advantage was taken of hydrostatic head to prevent effervescent loss of oxygen.

The District (Metropolitan Water Reclamation District of Greater Chicago, 1977) has considered utilizing U-tubes for deep reservoir oxygenation. Various aeration cases were considered. Using drop shafts for oxygen injection did not provide enough velocity to entrain oxygen in three cases analyzed. A fourth case, using a separate U-tube adjacent to the drop shafts for oxygen transfer yielded a sufficient velocity (4 feet/second) within the tube to entrain oxygen and was deemed to be technically feasible. This envisioned individual U-tubes at selected drop shafts.

Problems Using U-Tubes for Deep Reservoir Aeration

1. In all cases where U-tubes were utilized, either a flowing stream or drop in water level were utilized for pressure through the U-tube. These conditions rarely exist in quiescent reservoirs.
2. Horizontal mixing would be more difficult in a deep reservoir than in a river or impoundment

where there is always some water movement past the discharge of the U-tube.

3. Horizontal mixing of the discharge would be more difficult in a holding reservoir than in an impoundment produced by damming a flowing stream.
4. Effervescence appears to be a problem in the U-tube effluent, when oxygen concentrations more than double the oxygen saturation value are exposed to the atmosphere.

CONVENTIONAL AERATION

Conventional aeration using fine or coarse bubble diffusers has been in use in the waste treatment field for over 100 years (Alleman and Prakasam, 1983).

Significant improvements in energy efficiency in diffused air systems are given including:

1. New types of fine pore diffusers and diffuser cleaning systems.
2. Changes in configuration of the diffusers in the aeration tanks.
3. Control systems for regulating operation of the aeration equipment that supplies DO to the aeration tanks.
4. Probes for the in situ measurement of DO.

The current plan for the McCook Reservoir calls for each stage of the two-stage reservoir to be aerated primarily with a diffused air system capable of a maximum flow rate of 22,650 standard cubic feet per minute (scfm) for each stage. Air would be delivered to a system of diffusers through a network of pipes laid on the reservoir floor. Compressors would move the air through the pipe network to coarse diffusers. The following are a number of studies which may be useful in evaluating use of conventional aeration in deep reservoirs.

Wilhelms and Martin (1992) determined that gas transfer in a rising bubble plume is strongly affected by the hydrostatic pressure which is a function of depth. Models of oxygen transfer and concentration must integrate the effect of pressure over the depth of the reservoir. They indicated that models needed to be verified in a test facility similar in depth to the reservoir to be aerated.

Thatcher (1992) found that, all else being equal, a higher density of diffusers would result in greater OTE.

The Tennessee Valley Authority (TVA) utilizes a diffused air or oxygen system at six hydropower projects, one TVA nuclear plant and two non-power reservoirs (Mobley, 1997). The low DO content of reservoir releases is often a problem. Oxygen can be added by means of either air or water, depending on the need. Location of diffusers deep in the reservoir allows for oxygen transfer efficiencies of up to 90 percent without thermal destratification of the reservoirs. A difference between the TVA installations and the proposed McCook Reservoir is the relatively low oxygen demand of most TVA reservoir waters. Oxygen demand is often less than 1 mg/l per day. In conditions such as these, relatively low delivery of air or oxygen is needed. The TVA has over 35 years' experience operating diffuser systems and uses ceramic diffusers, flexible membrane diffusers, porous hose diffusers, and line diffusers.

Flows up to 45,000 cfs have been aerated using diffuser systems. The TVA has found all these diffuser systems to be satisfactory.

The U. S. Army Corps of Engineers contracted to have a study performed on environmental aspects of artificial aeration and oxygenation of reservoirs (Pastorok et al., 1982). Some systems involved artificial destratification while others required aeration without destratification.

Wagner and Popel (1996) looked at the effects of diffuser submergence and density on oxygen transfer and aeration efficiency. They found that the volumetric oxygen transfer rate is higher with increasing depth of submergence at the same air flow rate. This was a result of greater hydrostatic pressure at lower tank depths. They also found higher oxygen absorption with increased diffuser density.

Johnson and McKinney (1994) found that there was a direct correlation to oxygen transfer and mixing. They also found that basin depth considerations were more important for coarse bubble diffusers than for fine bubble diffusers. Increasing basin depth had a greater effect on coarse bubble than fine bubble diffusers.

Wahl et al., (1994) found that compressed air aeration of turbine discharge was effective in increasing DO downstream from the aerators.

Problems with Available Conventional Aeration Studies

Most of these are similar to the problems with pure oxygen studies.

1. For aeration systems using coarse bubble diffusers, investigations conducted over relatively shallow depths demonstrated increased OTE over increased depth (ASCE, 1987). Price and Tillman (1991) performed a compilation of studies performed by a variety of investigators. They concluded that OTE using coarse diffusers could be estimated by a conservative linear regression using the worst case transfer for each depth:

   $$OTE\ (\%) = 0.6067z$$

   where z = depth of diffuser in feet. Thus for a reservoir depth of 150 feet, the OTE would be 0.6067*150 = 91%.

2. A portion of the increased transfer efficiency seen at increased depths is a result of increased pressure. An additional atmosphere of pressure is added every 34 feet of diffuser depth in water.

3. It appears likely that the bulk of the oxygen transfer in deep reservoirs takes place near the

bottom of the reservoir due to the increased pressure.

4. This is exactly what is required in most impoundments where the hypolimnion is where oxygen depletion takes place and where oxygen must be replaced.

5. In the absence of data of oxygen concentration at various depths, it would be necessary to perform deep aeration studies to assure that sufficient oxygen reached the upper depths of the reservoir.

COMPARISON STUDIES/INNOVATIVE PROCEDURES

There have been a number of studies in which several alternative aeration procedures have been evaluated.

The USEPA (Lorenzen and Fast, 1977) evaluated a number of methods for lake and reservoir circulation/aeration. These methods in general involved relatively low oxygen requirements. The oxygen depletion rates for the reservoirs described ranged from as low as 0.25 to 1.0 mg/l per week. In only a few lakes were the aeration requirements as high as 1 mg/l per day. Thus successful techniques for aeration of reservoirs and lakes may not always be directly comparable to impounded CSOs having a large oxygen demand.

Kim and Bohac (1989) compared several options for improving releases from the Fort Patrick Henry Dam on the South Fork Husston River in Tennessee. Stratification at the dam prevented cooler, denser water from replenishing its oxygen supply. Methods initially considered included turbine aeration, U-tube aeration, aerating weirs and high purity oxygen injection. They compared pure oxygen injection and turbine aeration with wasteload reduction and flow rate increase. They found the best method to increase stream DO was by a process of waste load reduction and flowrate increase.

Mobley (1990) evaluated the efficiency of oxygen diffusers in the Douglas Reservoir in Tennessee. He estimated the efficiency of aeration to be 50 percent to 70 percent in the reservoir which is approximately 100 feet deep.

Mobley, et al., (1995) were able to increase oxygen content of a hydropower plant discharge by 1.5 to 2.0 mg/l drawing water from the top of the same reservoir. Surface water pumps were used to move water to a depth where it would be withdrawn by hydroturbines. The high DO in the surface water provided additional oxygen to the hypolimnion.

A hypolimnetic aerator was described by Taggert and McQueen, (1982) as one which operates as a reverse U-tube. Compressed air was utilized to aerate the hypolimnetic water of the lake. An aerator at the bottom causes water to rise in the upcomer. The water travels through the tube and is discharged by the downcomer in a reverse of normal U-tube operations.

Rahmé et al., (1997) described methods of predicting oxygen uptake at enclosed drop structures. Drop height appeared to be the most important factor in oxygen addition. The mass transfer methods listed were

1. Free falling jet surface.
2. Droplets from disintegrating water jets.

3. Splashing generated at the tailwater surface by the impact of a falling water jet.
4. Agitated tailwater surface.
5. Air bubbles entrained in the tailwater.

The relative importance of each of these mass transfer mechanisms will vary from structure to structure. The authors also concluded that the oxygen transfer surface area associated with each structure was difficult to assess.

Hibbs et al., (1997) examined a series of DO enhancement systems for their ability to maintain a minimum DO concentration of 6 mg/l below the El Vado hydroelectric facility in northern New Mexico. Systems considered included surface axial flow pumps, a selective withdrawal tower, aerating weirs, and bubble diffusers in the forebay or tailrace. The most cost effective design was found to be an air injection system consisting of a high volume low pressure blower connected to an existing draft tube venting line, supplemented with pure oxygen as needed.

McQueen and Lean (1986) produced an overview of hypolimnetic aeration. They presented a summary table of aerators in use in a number of countries. Features commonly found included:

1. A vertical riser tube constructed of metal, fiberglass, or flexible polyvinyl situated at the

bottom and inside of a vertical compressed air diffuser head.

2. An air water separation chamber at the top of the riser.
3. Return tube leading from the separator to the hypolimnion.

Aerator design specifications were given as:

1. Volume.
2. Oxygen consumption.
3. Air water exchange efficiency.
4. Water flow rates.
5. Riser and return tube diameters.
6. Air flow requirements.
7. Compressor capacity.
8. Operation costs.

Fuss and Rastler (1990) described a utility guide published by the Electrical Power Research Institute (EPRI) for meeting DO limits for hydroelectric power plant discharges.

They found the following to be important:

1. Determination of site-specific conditions.
2. Identification of the applicable DO criteria.
3. Determine if the site is already in compliance.
4. Arrive at the best mitigation alternative.

The procedure includes the compilation of water quality data, recommendations as to monitoring systems, and agencies which could be involved in the process.

If the discharge from the site does not meet the prevailing DO standards, the procedure continues with the selection of a suitable aeration system. Systems can be compared in the areas of:

1. Working principles.
2. Sizing.
3. Limitations.
4. Environmental effects.
5. Life expectancy.
6. Possible modes of failure.
7. Installation costs.
8. Annual operation and maintenance costs.
9. Power losses.
10. Safety.
11. Economics.
12. State of knowledge.

The systems considered include:

1. Adjustments of operation.
2. Selective withdrawal.
3. Bypass systems.
4. Weirs.

5. Forced and natural turbine venting.

6. Epilimnion surface pumps.

7. Tailrace aeration.

8. Reservoir destratification.

9. Hypolimnion aeration.

10. Draft tube aeration.

11. Penstock injection.

12. Combinations of systems.

The guide also discusses the physics of gas dynamics.

Ungate (1991) discusses a five-year lake improvement plan for the TVA. DO levels in the bottom level of reservoirs, especially deep tributary reservoirs, were below the requirements for downstream fisheries. Specifics of aeration were not discussed. Minimum flows and aeration were emphasized.

Rodrigue et al., (1997) compared relative costs of six different methods of increasing oxygen concentrations in the Housatonic River in Connecticut.

These included:

Alternative	Relative cost
1. Reservoir destratification	1.0
2. Intake modification	2.8
3. Powerhouse expansion	3.4
4. Turbine air injection	3.9
5. Oxygen injection	4.6

6. Upper level withdrawal 4.6

The Reservoir Releases Task Force (1987) of the TVA discusses methods of increasing the DO content of reservoir releases. There was no rigorous economic comparison of methods, and procedures for increasing DO at the reservoirs were site specific.

Lewis and Bohac (1984) discussed the costs of reservoir release aeration alternatives at seven reservoirs. In all cases capital costs, power loss curves, and operating costs were site specific. In general, reservoir releases contained low BOD_5, and cannot be directly compared to a reservoir containing a BOD_5 of 50 mg/l.

<u>Problems with Comparison Studies</u>

Three problems make it difficult to draw conclusions from these studies:

1. In almost all cases, the major concern driving lake aeration/oxygenation was oxygen depletion in the hypolimnion.
2. With increased pressure at depth, the oxygen driving force (C*-C) increases, and oxygen is transferred to exactly where it is needed in these studies, the hypolimnion.

3. The main concern with the McCook Reservoir is DO at all depths with an emphasis on near surface DO concentrations.

OTE IN DEEP RESERVOIRS

Although not part of the original literature search, OTE in deep lakes was addressed in several of the studies examined. The data is presented in Table 3.

TABLE 3

OXYGEN TRANSFER EFFICIENCIES REPORTED IN SEVERAL ARTIFICIALLY AERATED DEEP RESERVOIRS AND LAKES

Reservoir Type	Depth	Aeration System	Oxygen Transfer Efficiency (Percent)	Reference
Richard B. Russel Dam	140 ft	Pure oxygen diffusers		Mauldin et al., 1988
Fine bubble			80	
Coarse bubble			50	
Cherokee Dam	140 ft	Line diffusers	90	Mobley, 1997
(and others)	varying	(air or oxygen)	90	
Cherokee Dam (Mathematical)	140 ft	Line diffusers (air or oxygen)	80	Hadjerioum et al., 1995
Wahnbach Lake	70 ft	Not given	50	Taggert and McQueen, 1982
	138 ft	Not given	50	
Silver Lake	138 ft	Not given	45	Taggert and McQueen, 1982
	40 ft	Not given	23	

At depths greater than 130 feet oxygen transfer efficiencies of 50-90 percent have been regularly achieved in reservoirs.

COMPARISON OF COSTS

A number of studies yielded enough data to allow comparison among the three major methods examined. Often, as in a dam with a discharge with a low DO content, the BOD_5 was relatively low and an alternative other than the three main methods in this report turned out to be the most cost effective. These procedures, such as limiting discharge or reservoir destratification, are not included. Dam and corresponding hydropower discharges, in particular, often contain low DO but little BOD_5. The DO concentration in these can be readily increased by a variety of methods. Comparisons of conventional aeration, pure oxygen aeration and U-tube aeration costs are shown in Table 4. These studies concern transferring various amounts of DO at various initial and final concentrations, but are not directly applicable. With the exception of the reference paper by Macaitis (1990), all are based on actual costs or the costs are extrapolated from experimental data. The Macaitis reference includes only the estimated cost of oxygen.

Table 4

COMPARISON OF CONVENTIONAL AERATION, PURE OXYGEN AERATION, AND U-TUBE FOR COST EFFECTIVE OXYGEN TRANSFER

Discharge Type	Aeration System	Cost	Reference
Stormwater deep reservoir 70 mg/l BOD_5 900 ton/day demand	Cryogenic oxygen barge (Pure oxygen)	\$55/ton cost of oxygen	Macaitis, 1990
Hydroelectric generating impoundment	Pure oxygen injection	\$30/ton cost of oxygen	Speece et al., 1982
General costs Water quality uses	Oxygen generation		Speece et al., 1990
	5-20 tons/day	400 kWh/ton (\$36/ton)[1]	
	20-40 tons/day	400 kWh/ton (\$36/ton)[1]	
	>40 tons/day	400 kWh/ton (\$36/ton)[1]	
	Oxygen dissolution		
	downflow bubble		
	14.71 lbs/sq. in	500 kWh/ton (\$45/ton)[1]	
	75 lbs/sq. in	100 kWh/ton (\$9/ton)[1]	
	u-tube @ 60 mg/l	100 kWh/ton (\$9/ton)[1]	
	Conventional diffusion	550 kWh/ton (\$49.50/ton)[1]	
Pulp mill effluent to Tombigbee River	U-tube pure oxygen	94 Kwh/ton (\$8.46/ton)[1]	Speece, 1995

Table 4 (Continued)

COMPARISON OF CONVENTIONAL AERATION, PURE OXYGEN AERATION, AND U-TUBE FOR COST EFFECTIVE OXYGEN TRANSFER

Discharge Type	Aeration System	Cost	Reference
Simulated sewage	U-tube pure oxygen	$23/ton total cost	Speece et al., 1980
	Surface aerators	$42/ton total cost	
	U-tube pure oxygen	$6.50 absorbtion costs	
Stratified lakes	Air diffusers	$50-$100/ton amortised cost	Speece, 1994
	Pure oxygen Speece cone	$42.50 to $107.50/ton	

[1]$0.09/kWh.

CONCLUSIONS

Pure Oxygen Aeration

Pure oxygen aeration systems are generally used in applications where high DO levels and low mixing energy is required. Pure oxygen aeration systems have been used for reservoirs containing surface water, but no studies could be found where such systems were used for aerating stormwater and combined sewage in a deep reservoir with a BOD_5 similar to that for the McCook Reservoir. Most studies involve the use of pure oxygen aeration systems to supply DO to the hypolimnion of surface water reservoirs without causing destratification. Such studies cannot be extrapolated to the aeration requirements for the McCook Reservoir.

Surface water reservoirs have very low BOD_5, do not require mixing to prevent solids deposition and the top layers do not require significant DO to prevent odors; the opposite is true of the McCook Reservoir.

U-Tubes

U-tubes are generally used in applications where DO concentrations near saturation are required and where high hydrostatic head is available thus saving on U-tube pumping costs. The scientific literature contained no studies using U-tubes to aerate stored combined sewage and stormwater stored in a deep reservoir. U-tubes have been used to aerate reservoirs and rivers containing surface water, but these applications cannot be extrapolated to the aeration requirements of the McCook Reservoir. Aeration of a flowing stream using U-tubes does not require the input of large amounts of mixing energy to distribute DO throughout the water column and streams have a low BOD_5 level. As noted above, the aeration requirements of surface water reservoirs are not comparable to the aeration requirements of the McCook Reservoir.

Conventional Aeration

Conventional aeration using coarse or fine bubble diffusers and compressed air (from blowers) is generally the method of choice for maintaining DO in wastewater or combined sewage with BOD_5 levels similar to that for the McCook Reservoir. Conventional aeration is economical, easy to maintain and imparts large amounts of mixing energy needed to distribute DO and keep particulates in suspension. However, no studies could be found where conventional aeration was used to aerate combined sewage and stormwater in deep reservoirs. Conventional aeration has been used to aerate rivers and reservoirs containing surface water, but as noted previously these applications cannot be extrapolated to the aeration requirements of the McCook Reservoir. Therefore, direct information is not available in the scientific literature to select conventional aeration design criteria for the McCook Reservoir.

Overall Conclusion

Aeration of deep reservoirs and impoundments is an accepted technology for providing DO to deep waters in reservoirs. A variety of techniques are available to accomplish this objective. None of these technologies, however, are directly applicable to a reservoir of varying depths containing CSOs in which maintaining adequate DO in the upper layers of water is the primary concern.

RECOMMENDATION

There is a lack of direct information in the scientific literature on the use of pure oxygen, U-tube and conventional aeration systems to provide mixing and aeration of combined sewage and stormwater stored in a deep reservoir. None of the technologies reviewed are directly applicable to a reservoir of varying depths containing CSOs in which maintaining adequate DO in the upper layers of water is the primary concern.

Thus, further experimental and/or theoretical work may be required in order to design the McCook Reservoir aeration system.

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