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Liquid oxygen injection to increase dissolved oxygen concentrations in temperate zone lakes

By:
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Liquid Oxygen Injection to Increase Dissolved Oxygen Concentrations in Temperate Zone Lakes

Management Perspective

A simple process of oxygen injection into lake water was first tested in Hamilton Harbour. This paper discusses some of the results of its later use in Amisk Lake, Alberta and two sites in the USA. The eutrophication of Amisk Lake was reduced while its fishery was enhanced. The treatment continued for five years by cooperation of Alberta governments, University of Alberta and NWRI. However, local taxes of the small community could not support the continued treatment. The technology continues to be used effectively by Golder Associates in Onondaga Lake, and Irondequoit Bay, New York.

Abstract

Liquid oxygen injection (LOI) is a technology developed to increase dissolved oxygen in the hypolimnion of thermally stratified lakes while maintaining thermal stratification. This technology was developed as a cost-effective alternative to traditional hypolimnetic aeration technology that uses air to increase dissolved oxygen. LOI involves adding pure oxygen to the bottom of lakes through microporous spargers which causes high dissolution efficiency of the oxygen from the bubbles to the surrounding water. Dissolution efficiencies have been as great as 98%. This paper describes the engineering and installation requirements of a typical LOI system; results of three installations in North America are described. The information contained in this paper is sufficient to conceptually design a LOI system for use in lakes where dissolved oxygen concentrations are low and require treatment.

Key Words: lake restoration, oxygen

Injection d'oxygène pur pour augmenter les concentrations d'oxygène dissous dans les lacs de la zone tempérée.

SOMMAIRE À L'INTENTION DE LA DIRECTION

Un procédé simple d'injection d'oxygène pur (*liquid oxygen injection*)dans un lac a été essayé pour la première fois dans le port de Hamilton. Cet article examine quelques-uns des résultats obtenus lors de l'utilisation de ce procédé dans le lac Amisk, en Alberta, et dans deux sites aux États-Unis. L'eutrophisation du lac Amisk a été réduite et la pêche y a été meilleure. Le traitement s'est poursuivi pendant cinq ans, grâce à la coopération d'administrations albertaines, de l'Université de l'Alberta et de l'Institut national de recherche sur les eaux (INRE). Toutefois, les taxes de la petite localité étaient insuffisantes pour maintenir le projet en marche. Cette technique continue d'être utilisée avec succès par *Golder Associates* dans le lac Onondaga et la baie Irondequoit, dans l'État de New York.

Résumé

La technique d'injection d'oxygène pur (*liquid oxygen injection*) permet d'augmenter l'oxygène dissous dans l'hypolimnion des lacs à stratification thermique, tout en maintenant cette dernière. Cette technique a été mise au point pour remplacer la plus coûteuse technique traditionnelle d'aération hypolimnétique qui utilise l'air pour augmenter l'oxygène dissous. Elle consiste à ajouter de l'oxygène pur (converti de la phase liquide à la phase gazeuse avant injection) dans le fond des lacs à l'aide d'aérateurs microporeux assurant une dissolution très efficace de l'oxygène contenu dans les bulles. Les rendements de dissolution ont atteint jusqu'à 98 %. Cet article décrit comment construire et installer un système typique d'injection d'oxygène pur. De plus, les résultats obtenus dans trois installations en Amérique du Nord sont décrits. L'information contenue dans cet article est suffisante pour concevoir un système d'injection d'oxygène pur pour utilisation dans les lacs où les concentrations d'oxygène dissous sont faibles et où un traitement est nécessaire.

Mots-clés : restauration des lacs, oxygène

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Liquid oxygen injection to increase dissolved oxygen concentrations in temperate zone lakes

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1. Introduction

Many lakes and rivers throughout the world have low dissolved oxygen (DO) concentrations due to higher oxygen consumption than oxygen supply. Regardless of whether these low DO conditions are permanent or periodic, consequences include:

- high productivity caused by external nutrient loading or internal loading from the sediments (Mortimer, 1971; Mitchell and Prepas, 1990)
- decreased fish production (Frey, 1955; Fast *et al.*, 1975a)
- increased incidence of fish kills (Barica and Mathias, 1979)
- increased incidence of blue-green algal blooms, which may release compounds with taste and odour and toxicity (Kenefick *et al.*, 1992).

** Employee of Linde Union Carbide (Canada), now Praxair (Canada), when this work was performed*

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Numerous methods have been developed using air to increase DO concentrations in lakes. Two broad categories that cover most aeration systems are hypolimnetic aeration and destratification. 'Hypolimnion' refers to the deep layer in a thermally stratified lake. An excellent review of the general principles, engineering and applications of these two techniques is given in Cooke *et al.* (1993). Oxygenation is a relatively new method of increasing DO concentrations in surface waters that uses a pure oxygen source instead of air to increase DO concentrations in water bodies. This paper describes the technology of oxygenation using fine-bubble diffusers (spargers). We discuss the application, engineering, benefits and limitations, of this restoration technique. Finally, brief histories including installation, operation and results of LOI from three installations where oxygenation was tested at pilot and full-scale are presented. The critical new aspect of this work was the use of a simple diffuser system so that the capital cost of installation was modest thus enhancing the advantage of oxygenation start-up costs over those associated with aeration.

1.1 Background

Low DO concentrations are a consequence of numerous interrelated factors that affect many water bodies throughout the world. Most water bodies with low DO concentrations experience some or all of the following:

- thermal stratification or ice cover for prolonged periods;
- eutrophication;
- collapse of an algal bloom and;
- poor mixing during turnover events, such that thermal stratification is established before the lake becomes fully saturated with oxygen.

1.2 Hypolimnetic applications

Increased hypolimnetic DO is required under certain conditions to improve water quality and fisheries habitat. Application of any method to increase DO should be undertaken if some, or most, of the following conditions exist:

- external sources causing hypolimnetic anoxia/hypoxia are controlled as much as possible;
- internal loading of nutrients is a significant source of the total nutrient loading to the lake;
- low oxygen suppresses fisheries by restricting habitat and food.

Aeration/oxygenation systems are technical approaches to improve water quality. Ideally external nutrient sources are controlled and any other in lake remedial activities (such as flocculant addition) are concluded prior to using an aeration/oxygenation system to increase hypolimnetic DO. The chapter in this book by Ashley *et al.* reviews many aeration projects in naturally rich areas of British Columbia where nutrient sources could not be controlled. Similarly in Switzerland, human sewage was well controlled but management of farm manures was still a concern when their large oxygenation systems were implemented (Stadelmann *et al.*, 1984).

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There are both short and long-term operational requirements. During a single year, the system should be operated from the onset of thermal stratification until just before autumnal mixing, and again during the winter if low winter dissolved oxygen levels are a problem. The long-term requirements are unknown; in theory if external nutrients are controlled then internal nutrient loading and subsequent oxygen depletion could ultimately decline over time. This would result in a finite time period for artificial oxygen increasing; however, little information is available about the long-term requirement or sustainability of this remedial action. Gächter and Wehrli (1998) stated that ten years of oxygenation did not reduce sediment phosphorus release, but Prepas and Burke (1998) observed a significant reduction of sediment phosphorus release. Presumably site to site variation in aeration effectiveness will reflect differences in external loading, primary production, sedimentation, sediment particle size, mineral formation in sediments, groundwater, water circulation and other factors.

1.3 Aeration systems

Typical aeration systems use air as the source of oxygen to increase DO concentrations directly in the hypolimnion or mix and destratify the water. The general principles of these two systems are given below.

1.3.1 Hypolimnetic aeration

Hypolimnetic aeration is designed to increase the DO concentration of the hypolimnion while maintaining thermal stratification to: 1) decrease internal loading of phosphorus, an important limiting nutrient for algae; 2) improve fish habitat, particularly for cold water species and; 3) improve water quality for municipal water supplies.

Numerous methods are available and they can be categorized into either mechanical agitation or air lift systems (Cooke *et al.*, 1993). During mechanical agitation, water is removed from the lake, mixed turbulently in air to increase DO concentrations (such as with splash basins or mechanical mixers), then the hypolimnetic water is reintroduced into the hypolimnion. Air lift systems add compressed air at depth that forces water to the surface (full-lift system) or a pre-determined distance (partial air-lift system) (Figure 1). Re-aeration occurs from turbulent mixing with air bubbles (partial and full-lift system) and with air on the water surface (full-lift system).

The efficiency of hypolimnetic aerators is sometimes a problem. Gas transfer efficiency can be expressed as the ratio of the partial pressure of oxygen in the gas bubble to the partial pressure of oxygen in the water. Since air only contains 20% oxygen, the gas transfer efficiency is poor (approximately 2.5%$\cdot$m^{-1}). Consequently, large amounts of air have to be used to achieve relatively high DO increases, which can lead to nitrogen supersaturation and gas bubble disease in fish. Further, hypolimnetic aeration is more efficient in deeper lakes – the deeper a lake the greater the contact time of bubbles and therefore the greater absolute gas transfer. Thus, hypolimnetic aeration is not suitable for shallow lakes.

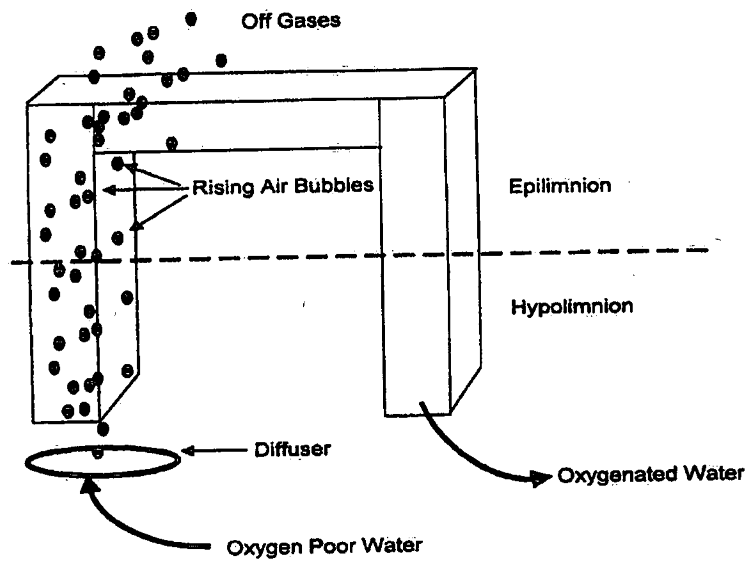

Fig 1. Full (top) and partial (bottom) hypolimnetic aeration system.

1.3.2 Destratifiers

Destratification is a method to breakdown thermal stratification in a lake, maintain circulation and thus aerate the entire lake volume at the surface. Destratification is achieved by causing turbulence throughout the lake, which mixes the lake water from top to bottom thereby destroying the thermocline. Typical methods of destratifying lakes include large bubble aeration and mechanical mixing devices.

Destratification systems tend to increase water temperatures by drawing warm surface waters to deeper depths which can reduce or eliminate cold water fish habitat. In addition, undersized systems may increase DO depletion because they cannot compensate for the higher oxygen demands caused by stirring up bottom sediments. In extreme situations, destratification systems can increase turbidity and diminish the aesthetics of the lake.

1.4 Summary of typical aeration systems

Hypolimnetic aeration and destratification systems have been shown to improve water quality in numerous lakes. However, both types of aeration systems have significant capital and ongoing costs with on-shore infrastructure and maintenance requirements (i.e. blowers, compressors, three-phase power). Many sites do not have adequate power supplies. In addition, gas transfer efficiency is poor, and noise and air pollution from compressors in simple systems can reduce the aesthetics of recreational sites. Therefore, new techniques have been developed that mitigate these limitations.

2. Oxygenation

Oxygenation refers to the use
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Oxygenation systems fall into
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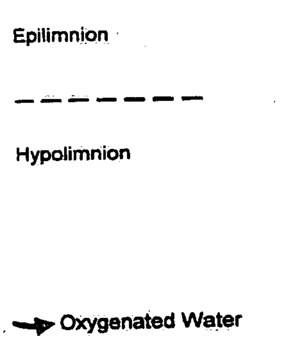

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2. Oxygenation

Oxygenation refers to the use of pure (>99%) oxygen as the gas supply to increase DO concentrations in water. Since pure oxygen contains 5 times more oxygen than air, gas transfer efficiency is increased by as much as 45 times and oxygen dissolution is faster. Oxygen dissolution from a gas bubble is a function of pressure; doubling the pressure increases dissolution by a factor of two. Similarly, diminishing the gas bubble diameter increases the surface area and subsequent dissolution rate. Oxygenation systems fall into two general categories: pressurized contact and fine bubble diffusers.

2.1 Pressurized contactor

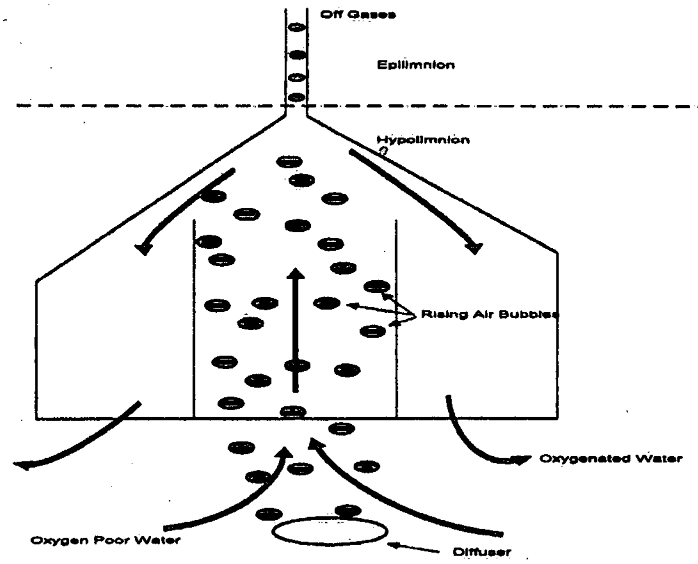
Pressurized systems bring oxygen into contact with water under pressure. Pressure is controlled by injecting oxygen-containing gases into deep water or by placing water under high pressure during oxygen contact. Pressurized contactors include pipeline reactors (sidestream pumping), floating tube contactors, or submerged mixers.

In sidestream pumping (*e.g.*, Fast *et al.*, 1975b), a stream of water is removed from the water body (typically a river or hypolimnetic water), pressurized with a pump, oxygenated, then returned to the lake (Figure 2). Oxygen dissolution efficiencies are high (>90%) and thermal stratification of the lake is maintained. This type of system is usually used for oxygenating water entering a lake for example, a waste stream with low DO concentration or rivers. This system has been used successfully in a large shallow lake in Washington State (Doke *et al.*, 1995).

A variation of a hypolimnetic aeration system can be made where pure oxygen is used for the gas supply instead of air. In this variation, oxygen instead of air is bubbled into the bottom of the "influent" tube and the water depth provides dissolution pressure. The oxygenated water then will flow down the "effluent" tube returning to the lake at depth, without disturbing thermal stratification (refer to figures 1 and 2) and increasing the hypolimnetic DO.

2.2 Fine bubble diffusers

LOI systems using fine bubble diffusers involves the formation of gas bubbles at depth in the water and allowing these bubbles to travel to the surface of the lake unencumbered by enclosures such as those associated with hypolimnetic aeration systems. Oxygen transfer is controlled by the oxygen gradient across the gas bubble, temperature, pressure, contact surface area (i.e. bubble size) and contact time. These controlling factors can be influenced by the pore size of the diffusers, structural design of the system and the depth of the diffusers. Large bubbles have a smaller surface area to volume ratio than small ones and rise through the water column more quickly. The large Swiss oxygenation systems worked well, but the diffusers were so large and heavy that a special boat with a large crane was required to service the diffusers (Stadelmann, 1988). Field trials with lighter tube-type diffusers have shown highest gas transfer efficiencies (>80%) at small (~20 μm) pore sizes (Nicholas and Ruane, 1979). Transfer efficiency also increases with depth and can be improved (i.e. for shallow lakes) by reducing the oxygen flow rate.



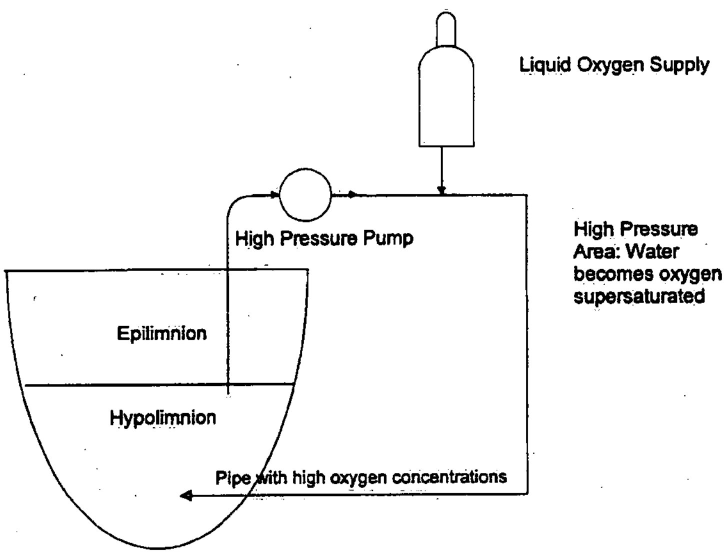


Fig. 2. Sidestream pumping. Water is brought to the on shore system and pressurized and liquid oxygen is added in the pipe. The oxygenated water is passed through a porous pipe into the hypolimnetic water with low oxygen concentration.

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3. Oxygenation methods

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3.1 Technical requirements

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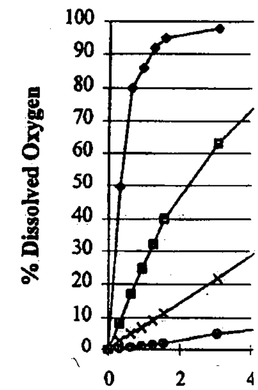
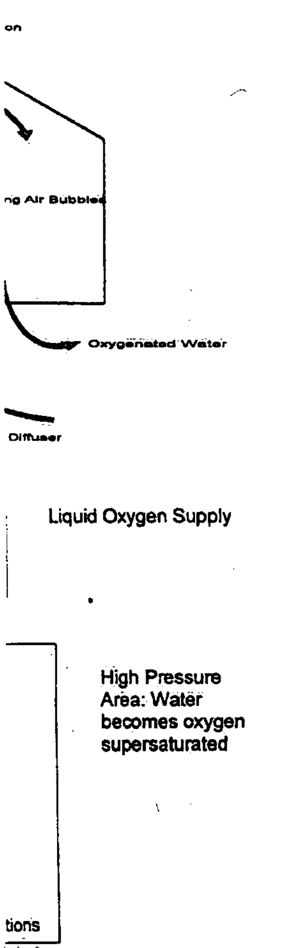


Fig. 3. Oxygen dissolution effici



c system and pressurized and liquid
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Thus, direct oxygen injection is efficient if the bubble diameter is small and depths are greater than 10 m (refer to Figure 3). The system requirements are quite modest: an onshore oxygen supply and a series of diffusers connected to the oxygen supply (Figure 4).

3. Oxygenation methods

Installation of fine bubble oxygenation systems was undertaken by the authors in three sites: Amisk Lake (Alberta), Irondequoit Bay (New York), and Onondaga Lake (New York). The main goal for each site was to increase hypolimnetic DO concentrations while maintaining thermal stratification during summer. Each oxygenation system was based on the same principle, although system size and configuration differed between sites.

3.1 Technical requirements

The following section reviews the hardware requirements for the oxygenation systems. Information regarding the installation and choice of materials is presented to allow the reader to appreciate the special requirements and considerations needed for this technology.

Each site for LOI systems will have different requirements based on the amount of oxygen required, estimated efficiency of the system, lake morphology, and number of diffusers.

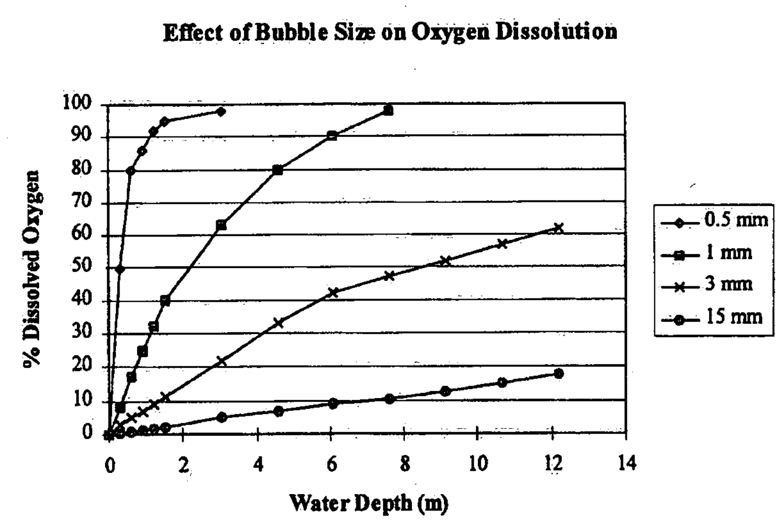

Fig. 3. Oxygen dissolution efficiency based on bubble size and water depth.

3.1.1 On-shore requirements

The on-shore components consist of a liquid oxygen tank, a vaporizer, flow controls and piping (refer to Figure 4). The oxygen tank stores the liquid oxygen and the flow meters control the delivery of oxygen to the diffusers. Most North American oxygen tanks are vertical towers which take little space but are highly visible. The Swiss utilized horizontal oxygen tanks that could be easily hidden behind farmers barns or hedges (Stadelmann, 1988). The liquid oxygen flows from the tank through a heat exchanger, which causes the liquid to vaporize and create pressure to force the gas to the offshore diffusers. The piping which carries the gaseous oxygen is usually buried between the onshore supply and the offshore hose to protect it from damage by vandalism and weather.

An alternative oxygen supply can be obtained through on site oxygen generation using a Pressure Swing Adsorption (PSA) unit. PSA units produce 90-95% pure oxygen *in situ* and can be sized for the site specific requirements.

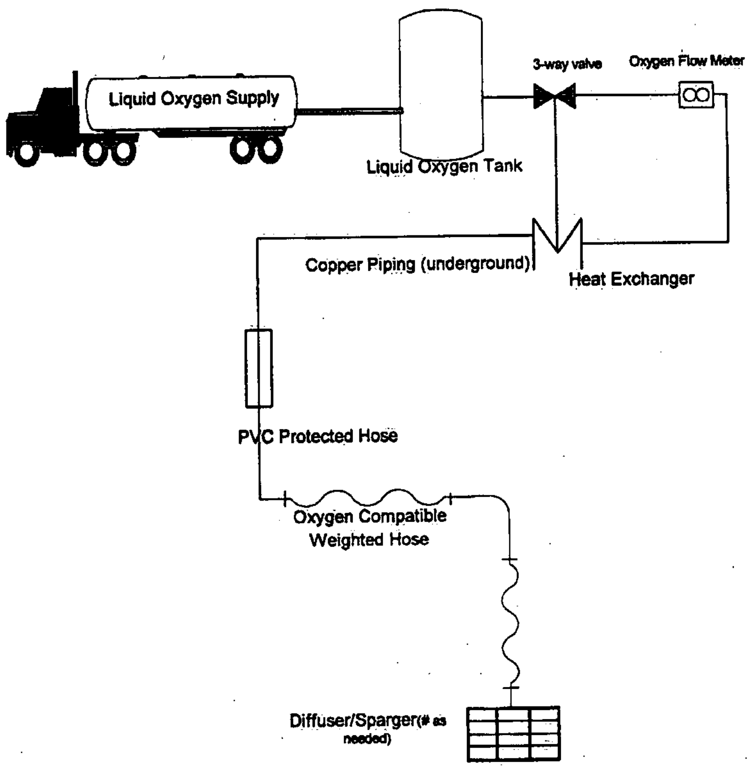

Fig. 4. Generalized schematic of a liquid oxygen injection system using tanjer deliverd liquid oxygen.

Designing a LOI system w
- road access for oxygen
- distance from regular l equipment (both for se
- proximity to the diffuse

3.1.2 Off shore hose

The offshore hardware con er the gaseous oxygen fro Oxygen-compatible rubbe taken by the authors.

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3.1.3 Diffuser

The diffusers function to the lake. The diffuser nee portation and installation, little manpower requirem structed from PVC piping forms the diffuser has to h
- produces fine bubbles,
- elastic so it won't brea
- inexpensive,
- can be cleaned,
- resists clogging.

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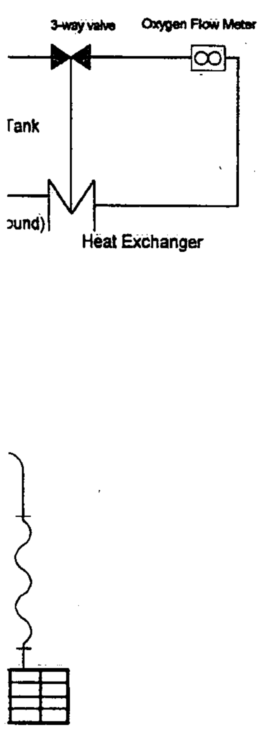

ı using tanjer deliverd liquid oxygen.

Designing a LOI system will require consideration of the following:

- road access for oxygen delivery trucks,
- distance from regular beach users but proximity to someone who can monitor equipment (both for security reasons),
- proximity to the diffuser sites to minimize the hose length required.

3.1.2 Off shore hose

The offshore hardware consists of hoses and diffusers. The hose is required to deliver the gaseous oxygen from the termination of the on-shore piping to the diffuser. Oxygen-compatible rubber hose has been used successfully in all projects undertaken by the authors.

The hose is sized for the maximum daily requirement of each diffuser. Hose usually is delivered in 500- to 1000-foot sections; the sections have to be joined securely to ensure there is no leakage. Experience has shown that male-male hose connectors secured with punch-lok clamps are the most appropriate connectors. Screw type connectors and standard hose clamps are unreliable and may leak.

The nearshore hose needs to be protected from damage by UV radiation and boats during the summer and from ice damage during the winter. Protection of the nearshore hose can be achieved by placing it inside a PVC tube; the rubber oxygen hose only needs to be protected to the maximum depth of ice (usually around 3 feet).

Since oxygen hose has a tendency to float, weights are required to keep it on the bottom. Re-bar (6.4 to 13 mm) attached to the rubber hose with nylon cable ties provides adequate weight. The re-bar spacing is dependent on the re-bar size and rubber hose size. The authors have found that with 19 mm I.D. rubber hose and 6.4 mm re-bar, a re-bar spacing of approximately 30 cm of re-bar for every 75 to 90 cm of hose is adequate.

3.1.3 Diffuser

The diffusers function to deliver gaseous oxygen bubbles into the hypolimnion of the lake. The diffuser needs to be strong enough to withstand the stress of transportation and installation, yet is has to be light enough to be able to be installed with little manpower requirements. The authors have found that a diffuser frame constructed from PVC piping attached to a metal stand is adequate. The material that forms the diffuser has to have the following characteristics:

- produces fine bubbles,
- elastic so it won't break,
- inexpensive,
- can be cleaned,
- resists clogging.

A material which meets the above criteria and which is readily available is Porex™. The diffuser is suspended approximately 75 cm above the sediments either with a series of anchors and floats or with legs built into a frame. The oxygen delivery hose is connected to the diffuser frame, ideally in the middle of the frame to provide equal pressure along each diffuser support length. A shut-off valve between the hose and the diffuser is required for installation of the system and to shut off gas flow in case diffuser repairs or cleaning are required. At the junction of each lateral length of tube, an orifice plate is installed to equalize the gas flow to each Porex™ supply tube. Each orifice plate is simple but must be custom-made, designed for the specific application and the daily gas requirement of each diffuser.

Thus, the number of diffusers required is dependent on the daily oxygen demand in the hypolimnion and on the lake morphology. More diffusers yield better distribution of the oxygen input but there is a compromise between cost and effectiveness.

3.2 *Installation*

Design, fabrication and installation of an oxygenation system is based on site-specific requirements. Daily oxygen requirement is calculated from the hypolimnetic (summer) or whole lake (winter) oxygen demand depending on when the oxygenation is required:

$$DOD = \frac{(DOt_1 - DOt_2)}{t_2 - t_1}$$

where DOD = daily oxygen demand (Tonnes)
DO = dissolved oxygen mass
t1 = time 1 (usually day 0)
t2 = time 2 (number of days past T1)

DOD calculation provides the minimum daily oxygen requirement. A safety factor of 20% additional oxygen of the DOD should be used in the final design. The system can be designed, taking into account the following site specific requirements:

- location of on-shore equipment,
- number of diffusers required,
- diffuser size and engineering (number of tubes, orifice size), etc.,
- diffuser support required (anchoring system).

The onshore equipment can be rented from and installed by the oxygen supplier, and the diffusers can be manufactured by a local mechanical contractor or the stakeholders themselves. Installation requires a minimum of two boats, adequately sized to hold the required equipment and personnel. The equipment is simple and light so that standard recreational boats of volunteers can be used for much of the work.

The locations of the diffusers in the lake are predetermined and marked with anchored surface floats. The hose is then connected to the onshore piping and laid out to the diffusers, with the hose weights added at appropriate intervals. At the diffuser location, the hose is connected to the diffuser, the system is tested for leaks and then the diffuser is lowered in place. The installation sequence is repeated as required. Sometimes more than one diffuser is connected to each supply hose. In these instances, the length of hose for each diffuser should be equal and the diffusers should be at the same depth to equalize the oxygen pressure at each diffuser.

4. Case histories

The following three case
improving water quality

4.1 *Amisk Lake, Alberta*

Amisk Lake (Table 1) recei
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4.1.1 Amisk Lake monitorin
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Table 1. Physical and Chemical

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Maximum Depth (m)	
Total Phosphorus (ug/L)	
Chlorophyll *a* (ug/L)	

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4. Case histories

The following three case histories illustrate the efficiency of LOI systems for improving water quality

4.1 Amisk Lake, Alberta

Amisk Lake (Table 1) received one of Canada's first whole-lake oxygenation treatments (Prepas *et al.* 1997). The Amisk Lake experience has been published as a series of papers (Canadian Journal of Fisheries and Aquatic Sciences, Vol. 54) and will only be briefly discussed here.

Amisk Lake has two basins. The shallower (30 m) north basin was oxygenated between 1988 and 1993. The first two years involved refining the equipment. During the remaining four years, oxygen was injected into the north basin of Amisk Lake year-round from two small diffusers anchored 50 cm above the sediments. The system was designed to add up to 1.3 Tonnes of oxygen per day to maintain hypolimnetic DO concentration above 2.0 mg/L during the summer and 5.0 mg/L during ice cover. The south basin of Amisk Lake and two other lakes from the area were used as controls.

4.1.1 Amisk Lake monitoring programme

Dissolved oxygen (Winkler titrations after Carpenter 1965), temperature, total phosphorus (Menzel and Corwin 1965) and chlorophyll *a* (Bergmann and Peters 1980) data were available from previous work on the three lakes. The lakes were monitored throughout the oxygenation test at Amisk Lake by researchers of the University of Alberta.

The DO goals were essentially met in north Amisk (refer to Figure 5). The minimum DO concentration was 5 mg/L in winter and 1.7 mg/L in the hypolimnion during summer stratification. There was a loss of about 83 tonnes of DO to the untreated basin during September to April (Lawrence *et al.* 1997) and a total of 150 tonnes in the last 4 years of the study (Prepas and Burke 1997). This DO loss therefore diminished the efficiency of the system (Lawrence *et al.* 1997). Stratification was not disrupted, but the volume of the hypolimnion of the north basin was increased by treatment. The temperature of the hypolimnion increased by more than 2C (Prepas and Burke 1997). Internal nutrient loading was decreased; the mean concentration of total phosphorus in the hypolimnion declined by more than 50%. Chlorophyll a concentrations decreased in the surface waters of the entire lake by 55%.

Table 1. Physical and Chemical Characteristics of the Study Lakes.

	North Amisk Lake	Irondequoit Bay	Onondaga Lake
Lake Area (km^2)	2.33	6.79	12.0
Mean Depth (m)	10.8	3.45	10.9
Maximum Depth (m)	34.0	23.7	19.5
Total Phosphorus (ug/L)	32.0	n/a	65
Chlorophyll *a* (ug/L)	16.5	17.0	30

n/a- not available

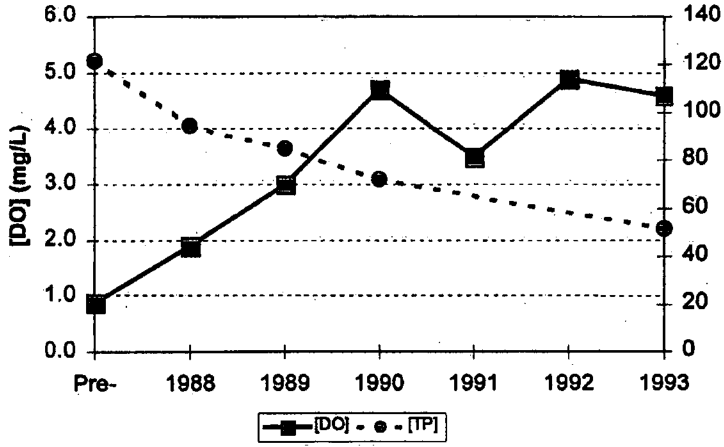

Fig. 5. Mean hypolimnetic dissolved oxygen (DO) and total phosphorus (TP) in Amisk Lake, Alberta.

4.2 Irondequoit Bay, New York

Irondequoit Bay (Table 1) is a large lake at Rochester, New York, that joins Lake Ontario through a very narrow and shallow channel. Irondequoit Bay has been subjected to liquid oxygen injection since 1993. Prior to the oxygen injection project the lake was treated with aluminum sulfate (alum) to precipitate the phosphorus. The alum application took place in 1986 and reduced hypolimnetic phosphorus accumulation from 28 to 6.6 kg/day.

The oxygenation system installed in Irondequoit Bay is more complex than that of Amisk Lake. Five diffusers (each with a capacity of a 1.0 tonne/day injection rate) were installed at various depths from 14 to 23 m. The system is operated when DO concentrations in the metalimnion fall below 4.0 mg/L normally during late June to mid-August. The system is shut off when fall turnover occurs.

The goals of the Irondequoit Bay oxygenation treatment were:

1. increase DO in the metalimnion and hypolimnion to create oxic condition for zooplankton, and
2. decrease or maintain the alum-reduced sediment phosphorus release rate.

4.2.1 Irondequoit Bay monitoring programme

Dissolved oxygen, total phosphorus and chlorophyll *a* were monitored to show the reaction of the large lake to LOI. Gas transfer efficiency was measured at each of the diffusers by collecting gas bubbles at the lake surface and analyzing the gas composition, and gas transfer efficiencies were calculated.

The thermocline has been maintained throughout the bay during the oxygenation project. Total phosphorus accumulation rates (Table 2) have been maintained at similar levels similar to those following the alum application.

Mean metalimnetic (July to September) DO has increased from <0.1 mg/L (prior to 1993) to 1.6 mg/L in 1997. 90% of fish captured were in the top 6 meters where

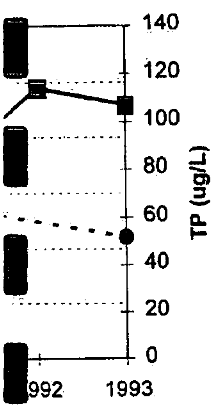

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Table 2. Total Phosphorus Hypolimnetic Accumulation Rates in Irondequoit Bay, New York.

Year	80-85	1986[2]	1987	1988	1989	1990	1991	1992	1993[3]	1994	1995	1996	1997
TPAR[1]	27.5	20	6.6	8.4	8.3	9.5	8.1	7.3	6.8	9.6	9.1	8.3	6.9

[1] Hypolimnetic total phosphorus accumulation rates (kg/day).
[2] Year Alum applied
[3] Year Aeration Project commenced

DO was more than 4 mg/L. Chlorophyll *a* has decreased from 17 mg/m^3 (1990-1992) to 11 mg/m^3 (1993-1997).

Based on data presented in Table 3 oxygen transfer efficiency ranged from 75 to 98%. The greatest transfer efficiencies were obtained from the deeper diffusers (longer contact time and increased *in situ* pressure) and later in the summer, when the greatest oxygen gradient existed.

4.3 Onondaga Lake, New York

Onondaga Lake (Table 1) is a highly eutrophic lake in Syracuse, New York. This lake was subjected to a pilot-scale oxygenation treatment inside a limnocorral (7.6 m diameter and 18.3 m deep). A single diffuser (consisting of 1 Porex™ tube) was installed at the bottom of the limnocorral and oxygen was added at an average rate of 4.4 kg/day. A second limnocorral identical to the experimental one was used as a control; and Lake Onondaga was monitored as well.

4.3.1 Onondaga Lake monitoring programme

Temperature, dissolved oxygen, phosphorus, chlorophyll a and Secchi disk depth were measured throughout the experiment.

The experiment showed that the thermocline was 1.9 and 2.4 m shallower than in the control corral and in the lake, respectively. The mean temperature of the oxygenated limnocorral during treatment was 0.6°C greater than in the control corral and in the lake.

Mean hypolimnetic DO increased in the treated corral from 0 mg/L prior to treatment to 9.1 mg/L within 2 days and further increased to a maximum of 44.1 mg/L at 15 m. During this period the hypolimnion of the control corral and the of lake were anoxic.

Mean total phosphorus decreased in the treated limnocorral slightly during the treatment period. After the liquid oxygen injection system was turned off mean total phosphorus decreased to 50% of the control and the lake. The implications of this delayed phosphorus decrease is that the fine current set up by the diffuser was able to transfer phosphorus from the hypolimnion to the epilimnion and maintain this phosphorus in the water column by the turbulence. This is attributed as an experimental artifact since the water does not have a chance to move laterally through the wall and then sink to the bottom and allow the phosphorus to precipitate.

Planktonic chlorophyll a concentrations were much lower in both the treated and control limnocorrals compared to the lake (Table 4). Secchi disk depth followed the same pattern wherein the treated and control limnocorrals had much higher Secchi disk readings than the lake (Table 5).

Table 3. Oxygen dissolution efficiency calculations in Irondequoit Bay, New York.

Date	Diffuser	Time (min)	Gas Volume Collected (L)	% of total gas collected (estimated)	Estimated rate of gas release from the water (L/min) (b/a/c)	Oxygen content of released gas (% vol)	Oxygen Volume released (L/min) (d*e)	Oxygen Injection[1] (ton/d/diffuser)	Oxygen Injection (L/min)	Efficiency (%) ((h-f)/h)
		a	b	c	d	e	f	g	h	i
Jun-24	1	5.25	12.5	11%	21.4	80%	17.20	0.64	304	94%
Jun-24	2	2.67	9.8	11%	33.0	70%	22.99	0.64	304	92%
Jun-24	3	4.85	5.2	11%	9.6	59%	5.66	0.64	304	98%
Jun-24	4	5.07	22.7	11%	40.3	65%	26.24	0.64	304	91%
Jun-24	5	6.18	15.5	11%	22.6	47%	10.52	0.64	304	97%
Jul-08	1	2.00	6	11%	27.0	82.7%	22.32	0.3	142	84%
Jul-08	2	2.00	8	11%	36.0	56.4%	20.31	0.3	142	86%
Jul-08	3	3.00	3	11%	9.0	52.1%	4.69	0.3	142	97%
Jul-08	4	1.75	10	11%	51.4	69.7%	35.83	0.3	142	75%
Jul-08	5	3.00	7.5	11%	22.5	60.1%	13.52	0.3	142	91%
Jul-22	1	4.00	7	11%	15.8	40.5%	6.38	0.32	152	96%
Jul-22	2	1.50	5	11%	30.0	39.0%	11.69	0.32	152	92%
Jul-22	3	3.00	4	11%	12.0	37.1%	4.45	0.32	152	97%
Jul-22	4	2.00	6.5	11%	29.3	30.0%	8.78	0.32	152	94%
Jul-22	5	2.00	5	11%	22.5	30.3%	6.81	0.32	152	96%

[1] 1 ton of oxygen/day = 24,150 ft^3/day = 16.77 ft^3/min = 474.9 L/min

Jul-08	5	3.00	7.5	11%	22.5	60.1%	13.52	0.3	142	91%
Jul-22	1	4.00	7	11%	15.8	40.5%	6.38	0.32	152	96%
Jul-22	2	1.50	5	11%	30.0	39.0%	11.69	0.32	152	92%
Jul-22	3	3.00	4	11%	12.0	37.1%	4.45	0.32	152	97%
Jul-22	4	2.00	6.5	11%	29.3	30.0%	8.78	0.32	152	94%
Jul-22	5	2.00	5	11%	22.5	30.3%	6.81	0.32	152	96%

[1] 1 ton of oxygen/day = 24,150 ft^3/day = 16.77 ft^3/min = 474.9 L/min

Table 4. Mean Chlorophyll a (ug/L) in Onondaga Lake in the oxygenated and control limnocorrals and the lake. During treatment (July 19 to August 17, 1993) and after treatment (August 18 to October 20).

	Treated Corral	Control Corral	Lake
During Treatment	24.3	38.1	56.8
After Treatment	3.9	5.59	26.1

Table 5. Secchi disk readings (m) in Onondaga Lake in the oxygenated and control limnocorrals and the lake. During treatment (July 19 to August 17, 1993) and after treatment (August 18 to October 20).

	Treated Corral	Control Corral	Lake
During Treatment	2.68	2.67	1.25
After Treatment	3.71	4.18	1.65

5. Costs

The cost for a liquid oxygen injection setup can be separated into the following major components.

1. Fixed onshore hardware (site preparation, tank, plumbing)
2. Fixed offshore hardware (diffusers, hoses)
3. Engineering and installation (design, manpower, boats etc.)
4. Oxygen.
5. Monitoring

The total cost is dependent on a number of factors including daily oxygen requirement, number of diffusers and, mainly, oxygen costs.

The following are estimated costs for the various components above (in $Can.):

Onshore Hardware: Tank rental, site preparation, plumbing supplied by oxygen supplier and may be incorporated into the oxygen supply costs. If priced separately, estimate tank rental (including plumbing) at $1,000/month and site preparation (cement pad and fencing) at $5,000.

Offshore Hardware: diffusers (1 tonne/day) at $5,000 each, hose, weights and clamps etc. at $7/m.

Engineering and Installation: $10,000 for the system design and $2,500/day for installation costs (includes manpower, boats etc.).

Oxygen Supply: estimated at $150/Tonne, but is dependent on the volume of oxygen required and the supplier.

Monitoring Costs: dependant on licensing and research requirements but estimated at $20,000. Can be minimized by cooperating with local universities and government labs.

There should be a yearly allowance of approximately $15,000 for maintenance and inspection of all the equipment. This could entail the use of professional divers to inspect the diffusers in operation.

The installation and maintenance costs can be minimized through the use of volunteers and supplying "in kind" equipment such as boats, anchoring material (rebar) and any other possible donations. The system design and fabrication should be carried out by professionals.

6. Conclusion

Liquid oxygen injection technology has been proven to efficiently increase DO in moderately deep temperate lakes in North America. Gas transfer efficiency ranges from 75 to over 95% and increases with greater injection depth and increasing oxygen concentration gradients.

The technology is relatively simple and can be manufactured easily to site specific requirements. The key components of the technology are the diffuser design and construction which should be undertaken by professional engineers who are accustomed to working with high pressure gases in aquatic environments.

7. Summary

Liquid oxygen injection (LOI) is a technology developed to increase dissolved oxygen in the hypolimnion of thermally stratified lakes while maintaining thermal stratification. This technology was developed as a cost-effective alternative to traditional hypolimnetic aeration technology that uses air to increase dissolved oxygen. LOI involves adding pure oxygen to the bottom of lakes through microporous spargers which causes high dissolution efficiency of the oxygen from the bubbles to the surrounding water. Dissolution efficiencies have been as great as 98%. This paper describes the engineering and installation requirements of a typical LOI system; results of three installations in North America are described. The information contained in this paper is sufficient to conceptually design a LOI system for use in lakes where dissolved oxygen concentrations are low and require treatment.

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