July 2004

Calfed Bay Delta Authority

# SAN JOAQUIN RIVER

## DISSOLVED OXYGEN AERATION PROJECT

Draft Engineering Feasibility Study

Prepared by
HDR Engineering, Inc.

HDR | ONE COMPANY | *Many Solutions* SM

# San Joaquin River Dissolved Oxygen Aeration Project

# Draft Engineering Feasibility Study

Prepared for:

**The California Bay-Delta Authority**

Prepared by:

**HDR Engineering, Inc.**

Folsom, CA

July 2004

# Table of Contents

# List of Figures

# List of Tables

# Acronyms and Abbreviations

| | |
|---|---|
| % | percent |
| °C | degrees Celsius |
| °F | degrees Fahrenheit |
| AOTE | Actual oxygen transfer efficiency |
| AOTR | Actual oxygen transfer rate |
| CBDA | California Bay-Delta Authority |
| cfs | cubic-feet-per-second |
| DWSC | Deep Water Ship Channel |
| DWR | Department of Water Resources |
| DO | Dissolved oxygen |
| ft | feet |
| ft/d | feet-per-day |
| ft/s | feet-per-second |
| hp | horsepower |
| JSA | Jones & Stokes Associates, Inc. |
| kW | kilowatt |
| kWh | kilowatt-hours |
| lbs/d | pounds-per-day |
| lbs/d-ft | pounds-per-day-foot |
| lbs/d-ft-length | pounds-per-day-foot-length |
| m | meter |
| mg/L | milligrams-per-liter |
| NMFS | National Marine Fisheries Service |
| NOAA | National Oceanic Atmospheric Administration |
| O&M | Operations and Maintenance |
| OMB | Federal Office of Management Budget |
| Port | Port of Stockton |
| psi | pounds-per-square-inch |
| RWQCB | California Regional Water Quality Control Board |
| SAE | Standard aeration efficiency |
| scfm | standard cubit-foot-per-minute |
| scfm/ft | standard cubic-foot-per-foot |
| SOTE | standard oxygen transfer efficiency |
| SOTR | standard oxygen transfer rate |
| TMDL | Total Maximum Daily Load |
| U.S. | United States |
| vs. | versus |
| yr | year |
| YSI | Yellow Springs Instrument |

# Introduction

The Port of Stockton (Port) Deep Water Ship Channel (DWSC), located in the San Joaquin River in the City Stockton, California and the County of San Joaquin, is the navigation channel used by ships traveling from the San Francisco Bay to the Port. The DWSC is approximately 78 miles long and terminates at the Deep Water Turning Basin adjacent to the Port. It is in the last in 12 miles of the DWSC, before reentering the Port, that insufficient concentrations of dissolved oxygen (DO) are present. Dissolve oxygen is a form of oxygen that is available for use by organisms living in the water. Insufficient concentrations of DO can result in the degradation of water quality, aquatic habitat and aesthetics. The purpose of this study is to consider mechanical aeration technologies, methods that add oxygen to waterbodies, identified by Jones & Stokes Associates, Inc. (JSA) in the *Aeration Research and Implementation Analysis Study for the Stockton Deep Water Ship Channel* (JSA 2004). Specifically, this Engineering Feasibility Study examines three mechanical aeration technologies identified by JSA including the 1) U-Tube, 2) Speece Cone, and 3) Bubble Plume.

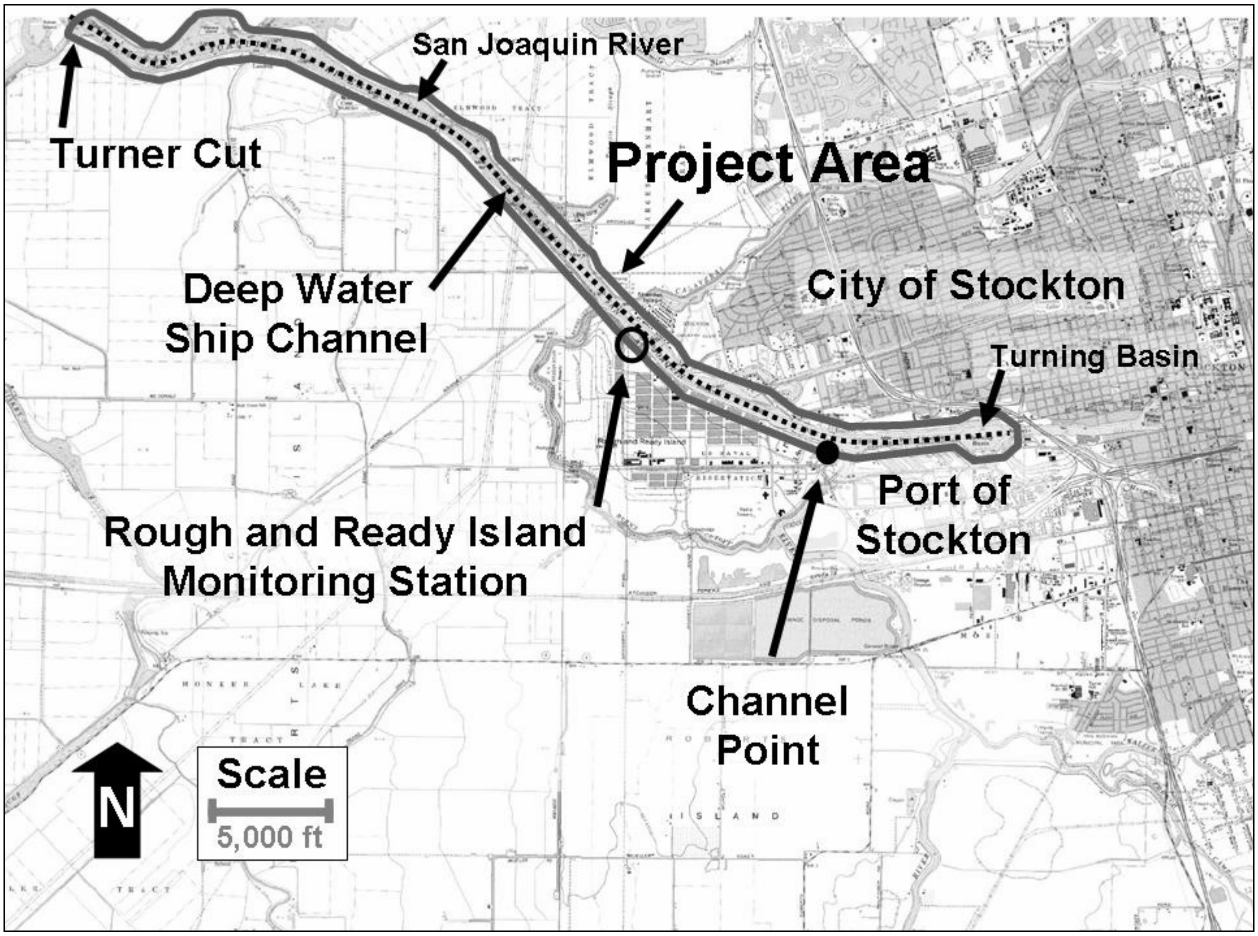
The first section of this study includes a discussion of the project issues and needs, and a presentation of the study scope. The second section provides a summary of existing conditions, including a discussion of the physical setting of the project and the resulting design criteria and key assumptions. Subsequent sections of this study present a description of each of the three technologies. The final section of the report presents a summary of the approach to development of alternatives, an evaluation and comparison of the alternatives considered, and conclusions regarding the performance of each alternative as it relates to the operational objectives of the study.

The information contained in this study will be used to assist the California Bay-Delta Authority (CBDA) and the California Regional Water Quality Control Board (RWQCB) in selecting a preferred aeration technology for implementation in the DWSC.

## PROJECT STUDY AREA

The Port is located along the San Joaquin River, in the southwestern portion of the City of Stockton, California just east of the confluence of the San Joaquin River and the DWSC (just east of where the river flows southeasterly through San Joaquin County). The project study area includes a 12-mile reach of the DWSC bounded on the west by Turner Cut, and on the east by the Port (see Figure 1).

**Figure 1. Project Study Area**




## PROJECT ISSUES AND NEEDS

Low DO concentrations ranging from 0.5 to 4.0 mg/L have been measured on an annual basis in the DWSC since 1983. Low DO concentrations in waterbodies may correlate with high algae and ammonia nitrogen concentrations, warm water temperatures, and low river flows, which often occur during summer months and periods of low precipitation. Primary impacts associated with low DO concentrations within the DWSC include, but are not limited to, the impairment of fisheries related resources. (RWQCB 2003)

The quality of water and aquatic habitat can be measured in terms of DO concentration and total maximum daily load (TMDL), which is a measure of the total pollutants a waterbody can receive and still meet water quality standards. The TMDL objectives applicable to the DWSC are regulated by the Central Valley Region of the RWQCB.

In 1994, the State of California placed the San Joaquin River on the Clean Water Act, Section 303(d) list, which establishes water quality standards and TMDL programs. Placement of the San Joaquin River on the 303(d) list was a result of repeated DO deficiencies in the DWSC. Dissolved oxygen levels continued to decline, and, in 1998, the State classified the issue as high priority for correction and established TMDL requirements for the DWSC. In response, a TMDL Implementation Program was developed by the RWQCB which specified that target DO levels in the San Joaquin River between Turner Cut and the Port should exceed 5 mg/L from December 1 through August 31, and 6 mg/L from September 1 through November 30 (RWQCB 2003). The Implementation Program suggested a three-tiered approach to solving the DO problem, which includes:

1. Enhancing DO levels within the DWSC using mechanical aeration techniques;
2. Reducing oxygen demand by decreasing nutrient sources from upstream water uses; and
3. Evaluating and mitigating the effects of channel deepening within the DWSC.

This Engineering Feasibility Study examines only mechanical aeration techniques for addressing DO issues (delineated as the first tier of the three-tiered-approach presented above). Mechanical aeration (or oxygenating water) has been shown to increase DO by:

- Adding oxygen directly to a waterbody via pure oxygen or oxygen within air;
- Adding oxygen-saturated water to a waterbody; or
- Mixing water to facilitate diffusion of atmospheric oxygen into the water. (JSA 2004)

Methods for mechanically oxygenating waters within the project area are presented in the *Evaluation of Aeration Technologies for the Stockton Deep Water Shipping Channel* (JSA 2003) and in the *Aeration Research and Implementation Analysis Study for the Stockton Deep Water Ship Channel Report* (JSA 2004). The 2004 study recommends that three technologies be considered for further evaluation and possible implementation. These technologies include U-Tube, Speece Cone, and Bubble Plume aeration.

## Study Scope

A summary of the study scope and work activities completed for this Engineering Feasibility Study is provided in Table 1.

**Table 1. Summary of Study Scope and Work Activities**

| Task | Description |
|---|---|
| Conduct literature search and review | Researched and reviewed available data, reports, and information for use in this study. |
| Establish design criteria and considerations for each of the three aeration technologies | Using published and observed field data, determined the appropriate range for operation and configuration parameters. Developed calculation spreadsheets to evaluate parameter sensitivity and finalize design criteria. |
| Prepare feasibility level designs of the three selected aeration technologies | Formulated preliminary alternatives for each technology that met project objectives. Evaluated tradeoffs. Selected a single alternative to represent each of the three technologies. |
| Complete feasibility level cost opinions for each alternative | Prepared feasibility level cost opinion and determined first capital costs, operation and maintenance costs, capital reoccurring expenditures, and annualized project costs. |
| Compare alternatives | Compared alternatives using a rating and scoring system and provided sufficient information for stakeholders to make an informed technology selection. |
| Prepare recommendations for future study/analysis and implementation of the selected alternative | Evaluated design considerations for each of the technologies. Developed recommendations for each technology for future evaluation and field verification as appropriate. |

# Existing Conditions and Discussion of Assumptions Used

The following section provides a brief summary of the results obtained from the field data review, existing background data, and literature search applicable to this Engineering Feasibility Study. Design criteria, configuration parameters, operating parameters, environmental parameters, general assumptions, and specific design considerations are identified and summarized. This section provides only those general items that are pertinent to all three technology evaluations. Technology specific parameters and design considerations are presented in the evaluation of each technology.

## PHYSICAL SETTING AND ASSUMPTIONS

### San Joaquin River Flow

On average, water flow through the DWSC ranges from 500 to 2,000 cfs with a hydraulic travel time of approximately 4 to 12 days between Channel Point and Turner Cut, (Foe, Gowdy, and McCarthy 2002). During the months of June through September flows are often observed as low as 250 cfs with travel times of approximately 32 days. Peak flows are observed in February and March with relatively low flows occurring June through December. For the purposes of this study, a minimum flow condition of 500 cfs is assumed within the San Joaquin River between Channel Point and Turner Cut.

### Hydrodynamics within the DWSC

The project area is tidally influenced with tidal stage fluctuations ranging from 0.25 feet below mean sea level to 4.25 feet above mean sea level. Without the influences of the tidal stage fluctuations, DWSC flows average 2,500 cfs (RWQCB 2003). As ebb flows gradually decrease, the flood tide raises water levels and reverses the direction of flow.

In November 2002, JSA performed a tracer (dye) study in the DWSC at the Rough and Ready Island dock to observe the flow characteristics of the channel, including velocity and dispersion rate. The purpose of the tracer study was to evaluate the potential area of influence of an aeration device operated within the DWSC.

The tracer study was conducted during a flood tide with flows of approximately 3,500 cfs and a velocity of 0.2 ft/s. After initial injection, the dye plume moved approximately one mile downstream then subsequently moved upstream near the injection point within 24 hours. Results from the tracer study show that it takes approximately 24 hours for complete lateral mixing to occur over a one mile long section of the DWSC (JSA 2003).

## Water Temperature

Oxygen demand is highly dependent upon increases in water temperature with oxygen depletion rates doubling with each 10 degree increase in temperature.

Water temperature is primarily affected by air temperature, but also relates to flow and channel configuration**.**

Measurements recorded in the DWSC, near Rough and Ready Island, indicate water temperatures ranging from 68 °F to 82.4 °F from June 1 through October 1 (reporting period 1983 through 2004) (JSA 2003, HDR 2001). For this study, a maximum limiting water temperature of 82.4 °F was used.

## Configuration of the DWSC

The depth of the San Joaquin River increases from 8 to 10 feet to 35 to 40 feet in the DWSC (Lee 2003). The width of the DWSC ranges from 600 to 700 feet. The velocity of water in the DWSC is slower than that in the river due to the increase in width and depth. This decreased velocity results in increased algal residence time and oxygen demand, and therefore, decreased DO.

For the purposes of this study, a depth of 25 feet is assumed for placement of aeration equipment to allow for variations in channel depth and to provide a 10-foot buffer.

## Dissolved Oxygen and Oxygen Mass Transfer

In general, DO is affected by water flow, water temperature, and channel configuration (depth and width) as described above. Insufficient DO concentrations can cause degradation of water quality and aquatic habitat.

Dissolved oxygen measurements have been taken by Department of Water Resources (DWR), City of Stockton, and others. Data indicates that DO concentrations fall below the minimum level during the months of July, August, September, and occasionally in October. In 2001, measurements at the Rough and Ready Monitoring Station (continuous monitoring at 15-minute intervals), indicated DO concentrations as low as 3 mg/L.

Oxygen requirements within the DWSC were calculated by JSA in *Evaluation of Aeration Technologies for the Stockton Deep Water Shipping Channel* (2003). Results indicate that the oxygen deficit was often 10,000 lbs/d with estimates of 15,000 lbs/d occurring sporadically. The JSA report suggests that a transfer of 10,000 lbs/d of oxygen would maintain the DO concentration above the minimum TMDL target of 5 mg/L (for the period of December through August). Introduction of 10,000 lbs/d of oxygen would therefore be sufficient for most scenarios observed within the DWSC and is used as an operating criterion for purposes of this study. The minimum TMDL target of 6mg/L for the period of September through November is not addressed in this study. An initial DO concentration of 5.2 mg/L is used as a trigger for beginning operation of starting the aeration technology to ensure that concentrations remain above 5 mg/L and a transfer oxygen rate of 10,000 lbs/d. It is also assumed that the maximum yearly oxygen transfer rate would be 1,000,000 lbs/yr of oxygen. That correlates to an annual operational period of 100 days.

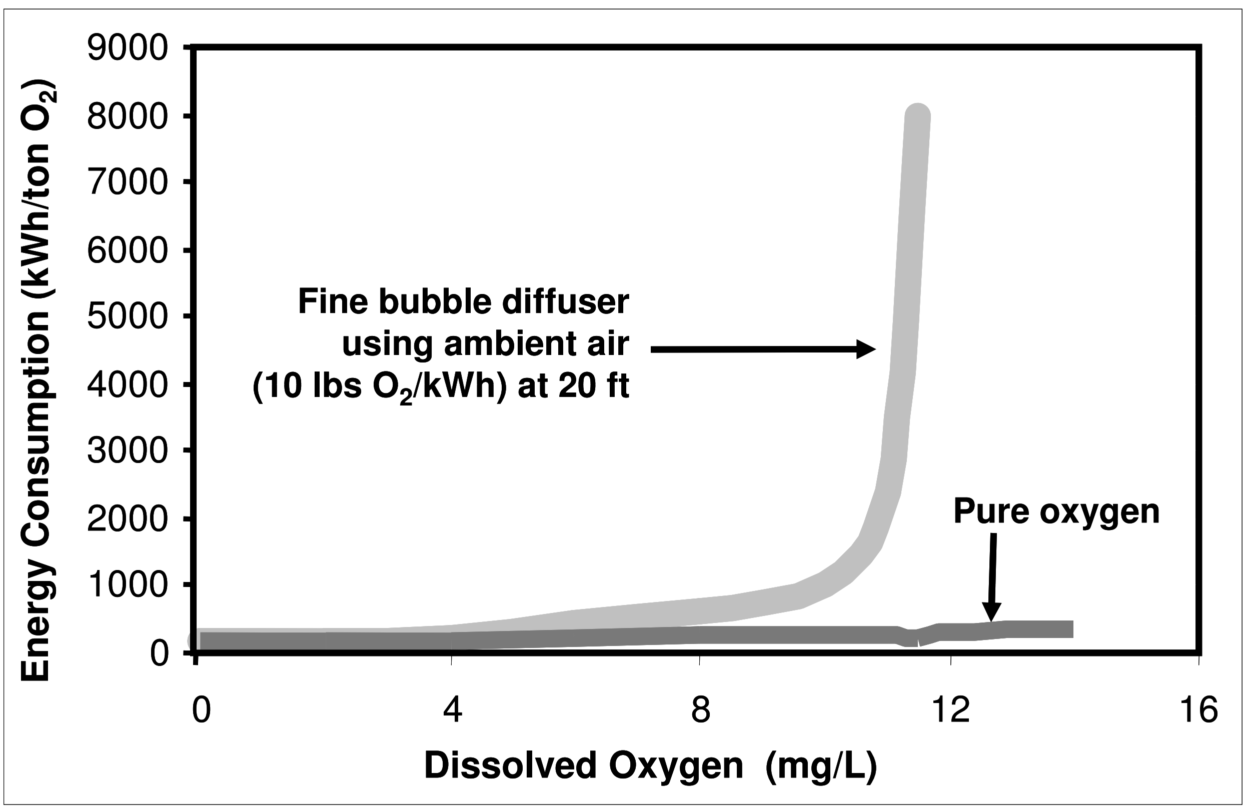
# OTHER KEY ASSUMPTIONS

## Selection of Oxygen Source

For purposes of consideration, each aeration device is required to accomplish an oxygen transfer rate of 10,000 lbs/d to off-set the oxygen deficiency that occurs in the DWSC. Oxygen sources for aeration devices can include ambient air, which contains approximately 20 percent oxygen gas by volume, and commercially available pure oxygen gas sources.

In general, the cost of energy to dissolve oxygen from air exceeds the cost of buying commercially-available oxygen when the target DO concentration exceeds 8 to 10 mg/L, assuming $0.06/kWh and $60/100 tons of oxygen (Speece 1996). Figure 2 shows the comparison of energy consumption per unit of oxygen transfer for systems using pure oxygen versus those using ambient air.

**Figure 2. Energy Consumption for Pure Oxygen vs. Ambient Air**




(Source: Speece E.R.1996)

In addition, the high percentage of nitrogen gas in the air and the large amount of air and water flows that need to go through the aeration system, if using air as the oxygen source, will cause high dissolved nitrogen concentration in water. Nitrogen ($N_2$) gas supersaturation can impair fish health and even cause death.

Therefore, for the purposes of this Engineering Feasibility Study, commercially available pure oxygen gas is used as the primary oxygen source. Air is evaluated only as an optional oxygen source when developing alternatives for the Bubble Plume aeration technology.

## Project Life

A project life of 20 years was assumed for this Engineering Feasibility Study.

## Discount Rate

The annual costs for each alternative must be discounted to account for the "real" time value of money. The Federal Office of Management and Budget (OMB) annually prescribes a discount rate for evaluating public infrastructure projects. For 2003-2004, OMB recommends a discount rate of 5.625 percent, therefore this rate was used in this study.

## Operation Period

An operation period of 24 hours/day (for 100 days/year) was deemed appropriate for this study for the following reasons: a) start and stop pump cycles, corresponding to shorter operation periods, would require additional control equipment increasing project costs, and b) conducting the oxygen injection over a 24-hour period allows for more of the oxygen gas bubbles to dissolve and reduces the amount of oxygen lost to the atmosphere.

The period of operation is assumed to be a maximum of 100 days of operation (based on a period when existing DO conditions fall below 5 mg/L) for 24 hours/day, which equates to 1,000,000 lbs/year of oxygen.

## Fish Screens

For aeration technologies that require pumping (i.e., U-Tube and Speece Cone), fish screens will be incorporated into the design to meet approach velocity and orifice sizing requirements set forth by the California Department of Fish and Game and National Oceanic Atmospheric Administration (NOAA) Fisheries (NMFS 1997).

## Navigation

It is assumed that the selected aeration technology, when implemented, will be fixed to the dock piers at the Port. The aeration device will be placed so that it has limited or no significant impact to navigation in the DWSC.

# SUMMARY OF GENERAL DESIGN CRITERIA AND KEY ASSUMPTIONS

Table 2 summarizes the general design criteria and key assumptions used throughout this Engineering Feasibility Study.

**Table 2. Summary of Performance Design Criteria and Key Assumptions**

| Criteria/Consideration | Value |
|---|---|
| Project Life | 20 Years |
| Discount Rate[1] | 5.625% |
| Operation Period | 24 hours/day for a maximum of 100 days/yr |
| Oxygen Mass Transfer | Daily: 10,000 lbs/d<br>Yearly: 1,000,000 lbs/yr |
| Operating Temperature of Water Column | 82.4 °F |
| Initial DO Concentration in DWSC | 5.2 mg/L |
| Equipment Placement/Depth of DWSC | Depth of 25 feet |
| Fish Screens | Used in U-Tube and Speece Cone technologies |
| Navigation | Limited or no impact to shipping vessels |
| Oxygen Source | Pure oxygen gas: U-Tube, Speece Cone<br>Ambient air: Bubble Plume |
| Minimum Flow Between Channel Point and Turner Cut | 500 cfs |

[1]Federal Office of Management and Budget (2004)

# Evaluation of Technologies

This section presents the approach used to formulate preliminary alternatives and select a single preferred U-Tube, Speece Cone, and Bubble Plume alternative configuration for further evaluation. The primary work conducted for this section includes:

1. A literature review for each aeration technology.
2. Development of general performance expectations based on literature review and available field data.
3. Establishing design criteria using information from literature search, available field data, with consideration given to local and regional water quality objectives – 10,000 lbs/d.
4. Development of spatial model, incorporating design criteria, which calculated values for system parameters (e.g., dissolved oxygen concentration can be calculated at any given depth throughout the U-Tube).
5. A sensitivity evaluation identifying correlations between and among system parameters.
6. Refinement of design criteria based on results from sensitivity evaluation.
7. An iterative process of modifying various configuration and operational parameters to maximize oxygen transfer efficiency and minimize costs. For the purposes of demonstrating potential tradeoffs resulting from modifying parameters, only a few of the many configurations considered as part of this Engineering Feasibility Study are presented. Parameters adjusted for each of the technologies are shown in Table 3.

**Table 3. Technologies and Adjusted Parameters**

| Technology | Parameter |
|---|---|
| U-Tube | Radius<br>Depth<br>Liquid flow rates<br>Oxygen gas flow rates |
| Speece Cone | Radius<br>Height<br>Liquid flow rate<br>Oxygen gas flow rate<br>Operating pressure |
| Bubble Plum | Oxygen source<br>Gas flow rate<br>Hose type |

8. Compared configurations based on tradeoffs and selected the preferred design configuration for each technology.

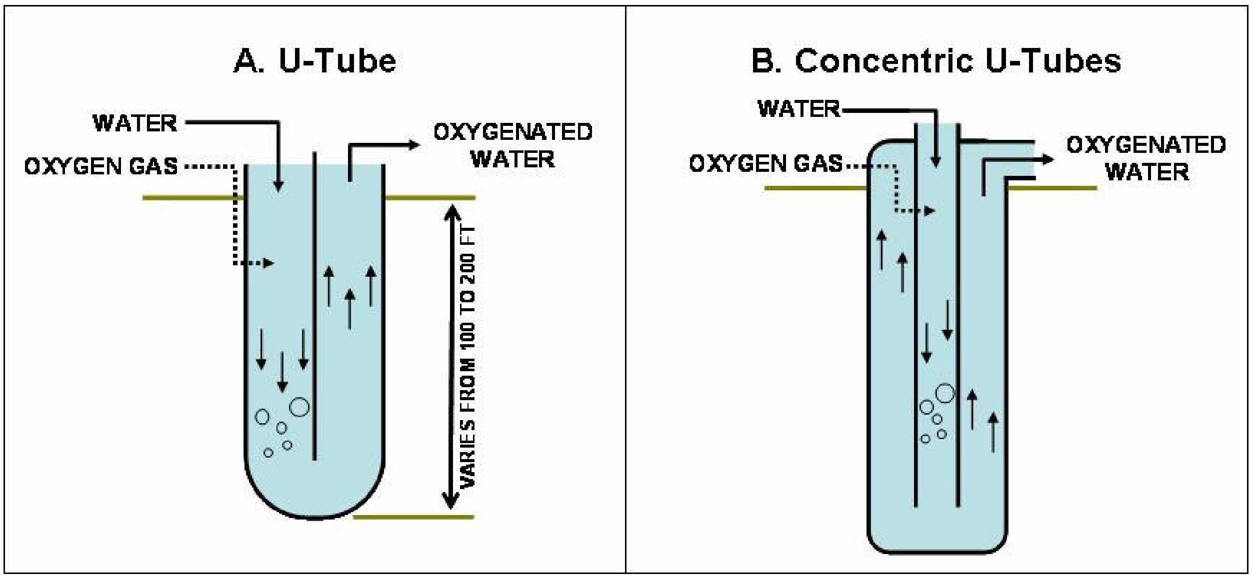
# U-TUBE

## Technology Overview

### *Configuration Description*

Two U-Tube configurations exist that could address the issue of low DO concentrations in the DWSC (see Figure 3). The first configuration is a U-shaped tube, with water and oxygen gas flowing downward into one side of the tube and oxygenated water flowing upward in the other side of the tube. The second U-Tube configuration consists of two concentrically aligned tubes or casings. A smaller, open-ended tube carries water and oxygen gas downward through the center of the casing. At the bottom of the tube, the water and oxygen mixture is released into the larger casing and is pushed back to the top of the U-Tube. Both configurations can be designed to be equally effective. For the purposes of this study, the concentric U-Tube configuration was evaluated.

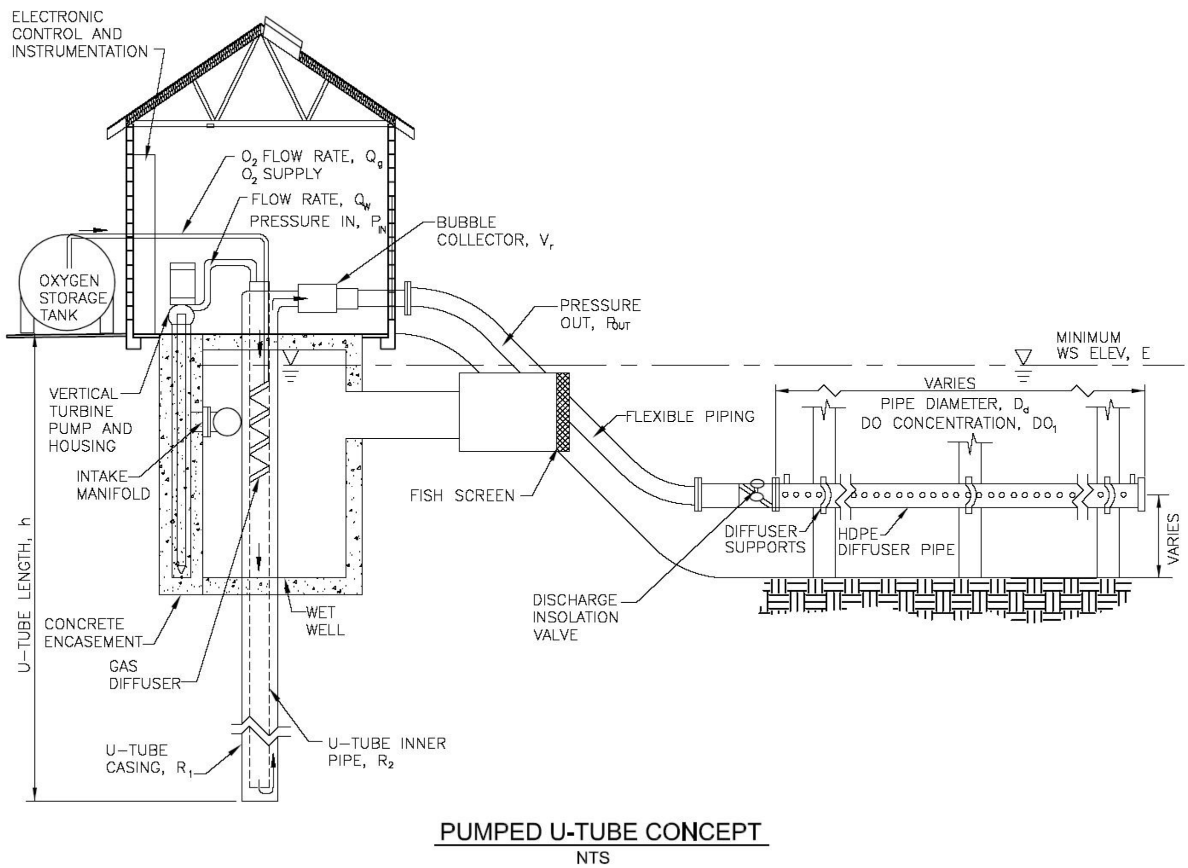
**Figure 3. U-Tube Configurations**




### *System Components*

A U-Tube DO aeration system usually consists of a U-Tube assembly, pumping equipment, oxygen storage tanks located above the water surface adjacent to the waterbody bank, fish screen, fine-bubble oxygen gas diffusers, and oxygenated water discharge diffusers or outfalls located beneath the water surface. Figure 4 depicts a schematic of a U-Tube system. The manner in which the system operates to accomplish oxygen transfer is discussed in the following paragraphs.

**Figure 4. Schematic of U-Tube System**




## *Oxygen Transfer*

The U-Tube enhances oxygen transfer efficiencies by subjecting water and oxygen gas mixture to increased hydraulic pressure as it travels deeper into the U-Tube system. In general, water and oxygen gas are pumped downward through the top of the smaller tube by emitting bubbles through a fine-bubble porous diffuser located approximately one-third of the distance from the top of the U-Tube inner casing. As the water travels downward through the tube at a calculated velocity, the oxygen gas bubbles are forced downward as well. Because bubbles that escape the downward flow of water will not be dissolved into the water stream, the target water velocity is set to 10 times that of a rising bubble. Assuming that a small bubble rises at 1 ft/s, the downward water velocity is therefore designed to be 10 ft/s. As the oxygen gas bubbles are forced to a greater depth and therefore, pressure, the oxygen gas bubbles are forced to dissolve into the pumped water. The result is an increase in DO concentration. The oxygenated water then travels upward to initial pressure and elevation. Here, it is immediately discharged via outfall or diffuser into the waterbody. As a result, the oxygenated water from the U-Tube transfers oxygen into the waterbody as the water disperses.

### *General Performance*

When in operation, the U-Tube has exhibited oxygen transfer efficiencies up to 95 percent and effluent DO concentrations of 40 to 50 mg/L while delivering 40,000 lbs/d of oxygen to the receiving water (Speece 1996 and 1993). A summary of the general performance expectations of a U-Tube aeration system is presented in Table 4.

**Table 4. General Performance Expectations of U-Tubes**

| Performance | Description |
|---|---|
| Discharge DO Concentrations | The U-Tube devise can be designed to produce effluent DO concentrations up to 50 mg/L when water is at or below 82.4 °F. |
| Oxygen Transfer Rate | By varying the configuration parameters of the U-Tube and/or the gas or water flow rates, daily oxygen transfer rates have been proven to range between 5,000 and 40,000 lbs/d. |
| Oxygen Transfer Efficiency | U-Tube configurations can be designed to obtain a transfer efficiency of up to 95 percent. That is, 95 percent of the oxygen supplied is dissolved into water. |
| Energy Consumption | Due to the fact that the pumping elevation is very similar to the discharge elevation, there is very little head loss through the U-Tube. Losses are only developed from pipe friction. Thus, energy requirements are typically less than other mechanical aeration systems. |

## Evaluation of Modified U-Tube Configurations

### *Oxygen Transfer Model Development*

For the purposes of this study, a model was developed to predict the oxygen bubble dynamics and oxygen transfer in a U-Tube for various configurations. The model is based on differential equations that govern the mass balance of both gas and water at different depths, configuration, and dimensions of a U-Tube. Most differential equations used for this study were adopted from the model developed for Speece Cone by McGinnis et al (1998) with some modifications and addition of equations by HDR. The model developed for this study simulates oxygen transfer, nitrogen stripping, and DO at any depth in a U-Tube and predicts oxygen transfer efficiency as a function of initial bubble size, gas and water flow rates, depth of operation and dimensions of a U-Tube.

The variables (or parameters) used in the model, their description and units used are listed in Table 5.

**Table 5. Variables and Parameters Used in U-Tube Model**

| Variable | Description | Unit |
|---|---|---|
| $c_i$ | Gas molar concentration in gaseous phase | mole/L |
| $C_i$ | Dissolved molar gas concentration | mole/L |
| h | Height of U-Tube | ft |
| $H_O$ and $H_N$ | Henry's Constant for oxygen and nitrogen gas | mole/$m^3$-Pa |
| J | Mass transfer flux across surface | mole/$m^2$-s |
| $K_{OL}$ and $K_N$ | Mass transfer coefficient for oxygen and nitrogen gases | ft/s |
| m | Molar flow rate of undissolved gas | mole/s |
| M | Molar flow rate of dissolved gas | mole/s |
| N | Number of air bubbles | quantity |
| $P_i$ | Partial gas pressure | psi |
| $Q_g$ | Gas flow rate | scfm |
| $Q_w$ | Water flow rate | cfs |
| R | Radius of U-Tube at any given depth z | ft |
| r | Gas bubble radius | ft |
| T | Absolute temperature | C |
| t | Time | s |
| V | Water flow velocity in relation to U-Tube | ft/s |
| $V_b$ | Gas bubble travel velocity in relation to U-Tube | ft/s |
| $V_s$ | Superficial water flow rate with gas mixture | ft/s |
| Z | Depth | ft |
| α | Correction factor for the effect of impurities in water on mass transfer coefficient | ratio |
| β | Correction factor for the effect of impurities in water on the saturated DO concentration | ratio |
| $\varepsilon_g$ | Fraction of gas per unit volume of water and gas mixture | fraction |
| Note: The model used for this Engineering Feasibility Study was developed using Metric System units. Where appropriate, results are presented in both metric and U.S. units. | | |

The correlations and mass balance equations used in the model development are presented in the following expressions.

$$V_s = \frac{Q_w}{\pi \times R^2} \quad (1)$$

$$V = \frac{V_s}{1 - \varepsilon_g} \quad (2)$$

$$\varepsilon_g = \frac{\Sigma C_i \times R \times T}{P_z} \quad (3)$$

$$\varepsilon_{g(0)} = \frac{Q_g}{\pi \times R_0^{\ 2} \times (V + V_b)} \quad (4)$$

$$dt = \frac{dZ}{(V + V_b)} \quad (5)$$

$$J = \alpha \times K_{OL} \times (\beta \times H \times P_i - C) \quad (6)$$

$$\frac{dM}{dZ} = \alpha \times K_{OL} \times (\beta \times H \times P_i - C) \times \frac{4\pi \times r^2 \times N}{(V + V_b) \times (1 - \varepsilon_{g(z)})} \quad (7)$$

$$N = \frac{Q_g}{\frac{4}{3} \times \pi \times r_0^{\ 3}} \quad (8)$$

$$M = \pi \times R^2 \times V \times C \quad (9)$$

$$C_z = \frac{M}{\pi \times R_z^{\ 2} \times V_z} \quad (10)$$

$$\frac{dm}{dZ} = -\alpha \times K_{OL} \times (\beta \times H \times P_i - C) \times \frac{4\pi \times r^2 \times N}{(V + V_b)} \quad (11)$$

$$m = \pi \times R^2 \times (V + V_b) \times c \quad (12)$$

$$c_z = \frac{m}{\pi \times R_z^{\ 2} \times (V + V_b)_z} \quad (13)$$

$$\frac{r}{r_o} = \left(\frac{m_{O2} + m_{N2}}{m_{O2(0)} + m_{N2(0)}}\right)^{\frac{1}{3}} \quad (14)$$

if r <7 x $10^{-4}$ m

$$V_b = 4474 \times r^{1.357} \quad (15)$$

if 7 x$10^{-4}$ <r <5.1x $10^{-3}$ m

$$V_b = 0.23 \quad (16)$$

if r >5.1 x$10^{-3}$ m

$$V_b = 4474 \times r^{1.357} \quad (17)$$

$$H_O = 2.125 \times 10^{-3} - 5.021 \times 10^{-7} \times T + 5.77 \times 10^{-9} \times T^2 \quad (18)$$

$$H_N = 1.042\times10^{-5} - 2.450\times10^{-7}\times T + 3.171\times10^{-9}\times T^2 \qquad (19)$$

$$K_{OL} = 0.6\times r \qquad (20)$$

if r < 6.67 x10$^{-4}$ m

if r > 6.67 x10$^{-4}$ m

$$K_{OL} = 4\times10^{-4} \qquad (21)$$

These equations describe the change in molar flow rate of gaseous oxygen and nitrogen in the undissolved phase, as well as the changes in molar flow rate of dissolved oxygen and nitrogen gases at any given depth. The set of differential equations comprising the model were solved using Euler's method.

### *Model Calibration and Validation*

The model was calibrated with full-scale field data of a U-Tube installed in the Tombigbee River in Alabama. The U-Tube configuration, operational conditions and field data were derived from Dr. R.E. Speece (1996). The U-Tube oxygenation performance was evaluated at three water flow rates - 46, 57, and 65 cfs - and an oxygen feeding range of 6,000 to 24,000 lbs/d. Key operational indictors recorded include water flow rate, oxygen feed rate, discharge DO, and pressure in down- and up-leg (i.e., tube radius). The discharge DO was measured using a Yellow Springs Instrument (YSI) DO meter. The YSI DO meter was equipped with a double thick membrane that enabled readable DO concentrations from 20 to 60 mg/L. A pressure chamber was custom-designed to allow sampling of the U-Tube discharge DO under pressure (15 psi is approximately 1 atmospheric pressure). The system configuration parameters are shown in Table 6.

**Table 6. U-Tube Configuration Used for Model Calibration**

| Parameter Description | Symbol | Value | Unit |
|---|---|---|---|
| Temperature | T | 82.4 | ºF |
| Elevation of water surface | E | 30 | ft |
| Operation depth-inlet | D | 35 | ft |
| Inner Tube radius (down-leg) | $R_1$ | 1.3 | ft |
| Outer tube radius (up-leg) | $R_2$ | 2.0 | ft |
| Tube height | $h_s$ | 174 | ft |
| Water flow rate | $Q_w$ | 45 to 65 | cfs |
| Gas flow rate at atmospheric pressure | $Q_g$ | 42 to 200 | scfm |
| Oxygen percentage in gas | $fo_2$ | 100 | % |
| Initial oxygen concentration in water | $C_0$ | 2.0 | mg/L |
| Correction for saturated DO | β | 0.95 | ratio |
| Correction for transfer rate | α | 0.80 | ratio |

**Figure 5. U-Tube Model Calibration: Oxygen Transfer Efficiency vs. Oxygen Feed Rate**

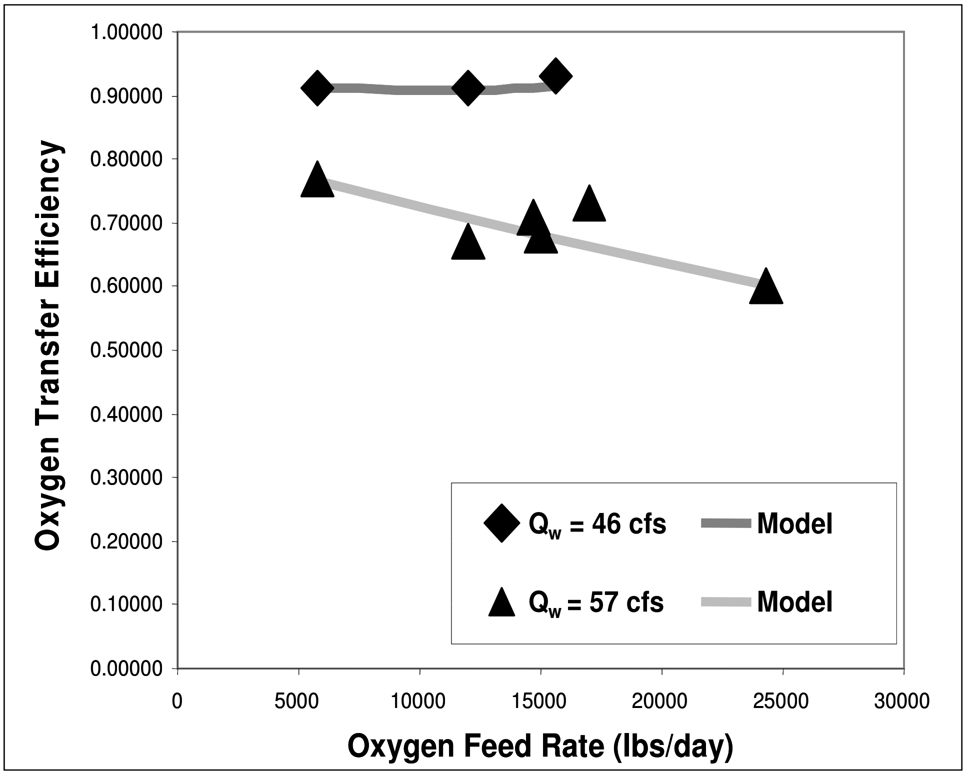



**Figure 6. U-Tube Model Calibration: Discharge DO vs. Oxygen Feed Rate**

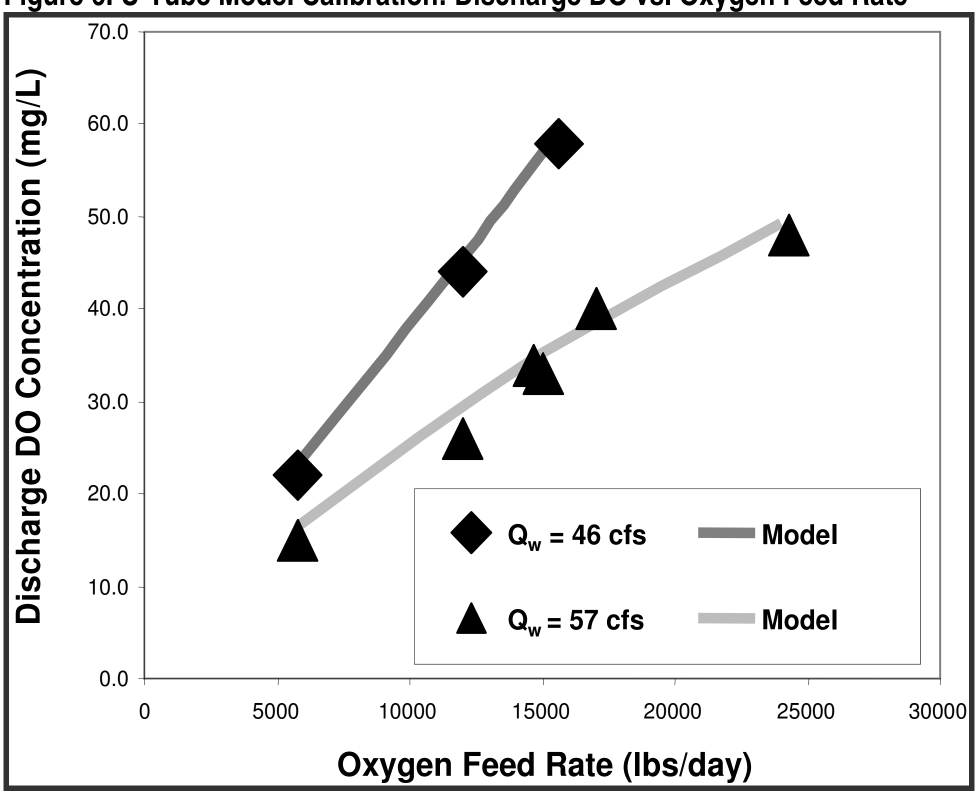


**Figure 7. U-Tube Model Calibration: Discharge DO vs. Oxygen Feed Rate**

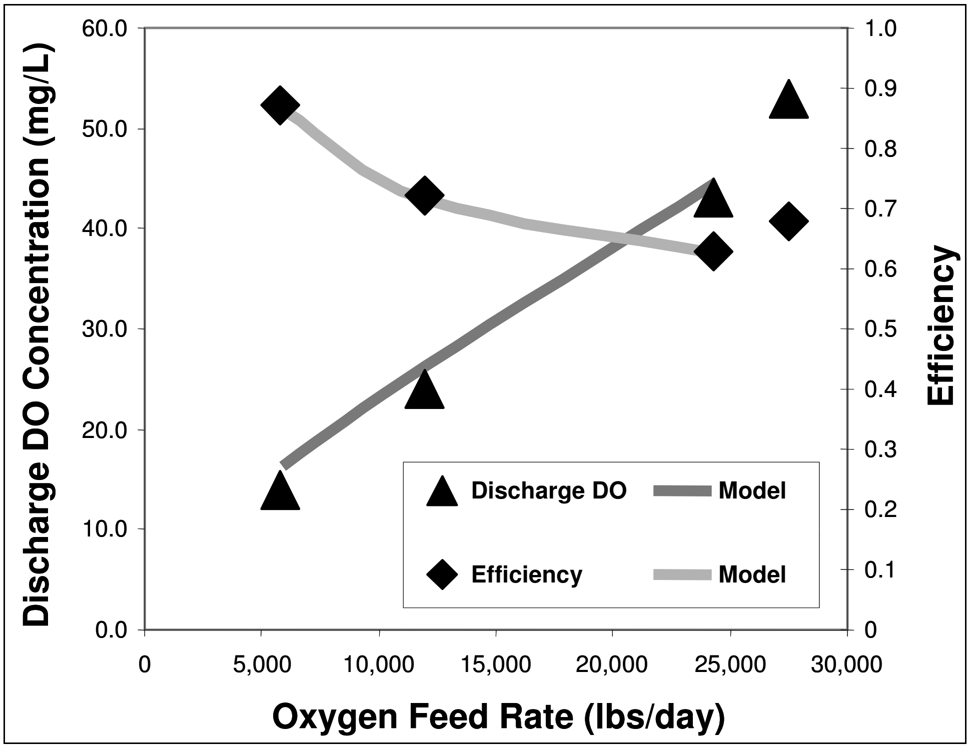
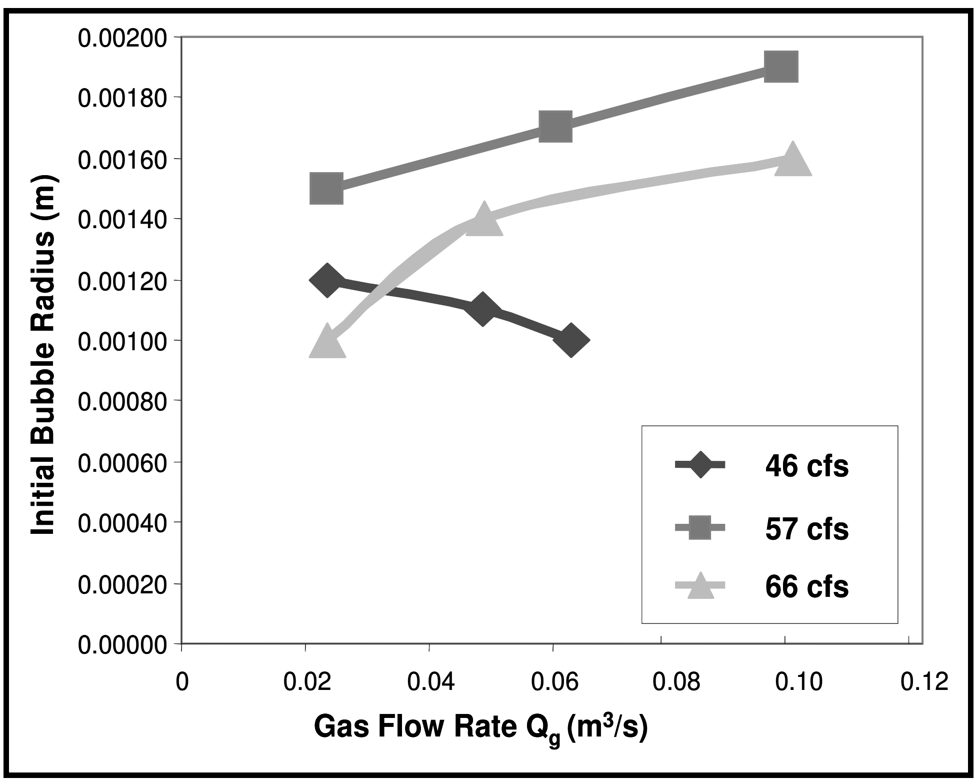



**Figure 8. U-Tube Model Calibration: Initial Equivalent Gas Bubble Size vs. Oxygen Gas Flow Rate and Water Flow Rate**



Application of the model simulation results to the field data are shown in Figure 5, Figure 6, and Figure 7. The model was calibrated to best correlate with the field data by changing only the initial equivalent gas bubble size using the calibration as shown in Figure 8. The equivalent initial gas bubble size can be interpreted as the calculated bubble size, assuming all gas bubbles are uniform. This establishes the equivalent gas-liquid boundary layer area as that in the field under certain operational conditions. The oxygen transfer efficiency is greatly affected by the initial equivalent gas bubble size, which is determined by the diffuser size and type, gas and water flow rates and the gas and liquid hydraulic mixing efficiency. The correlation of the model simulation results to the field-measured data demonstrates that the model is able to simulate the oxygenation performance of U-Tube well at the given operational conditions.

### *Basic Assumptions and Design Criteria*

The design criteria and conditions for U-Tube evaluation are summarized in Table 7. The rationale for use and sources of the selected design condition are described below.

**Table 7. Preliminary Design Criteria and Conditions for U-Tube.**

| Description | Symbol | Unit | Design Range |
|---|---|---|---|
| **Device Configuration** | | | |
| U-Tube outer radius | $D_1$ | ft | 1 to 3 |
| **Operational Conditions** | | | |
| Water flow velocity | V | ft/s | 10 |
| Gas (oxygen) rate-to-water flow rate ratio | $Q_g/Q_w$ | % | 2 to 5 |
| Hydraulic retention time | t | s | 50 to 60 |
| Initial bubble radius – oxygen inlet diffuser size and type | $r_0$ | Ft | .006 to .010 |
| Oxygen transfer coefficient | $K_{OL}$ | ft/s | f (D, α, bubble size) |
| Gas transfer/coefficient | $K_{L-a}$ | 1/s | f (diffuser, depth) |
| Nitrogen transfer coefficient | $K_{NL}$ | ft/s | f (D, β, bubble size) |
| Water velocity | $V_w$ | ft/s | 10 |
| Oxygen transfer efficiency | e | % | 50 to 90 |
| Head-loss through U-Tube | $h_L$ | ft | 5 to 6 |
| Correction coefficient for saturation DO | α | ratio | 0.90 |
| Correction coefficient for transfer rate | β | ratio | 0.95 |
| Oxygen concentration at discharge | $C_{O2,OUT}$ | mg/L | 40 to 50 |

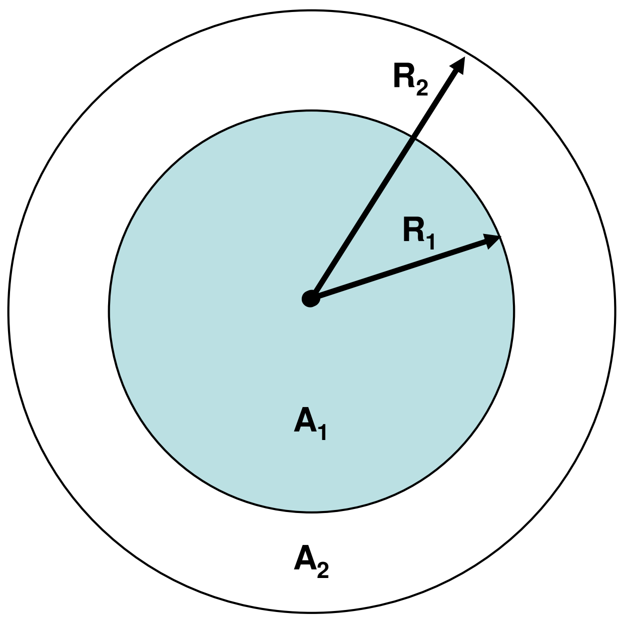
#### Design Down-Tube Velocity

The U-Tube oxygenation device is not widely used; therefore, only limited field data and experiences are available. Field data were obtained from a 4-foot-diameter full-scale U-Tube installed at Tombigbee River in Alabama by Dr. R.E. Speece (1993). In his report, Dr. Speece recommends a water velocity of about 10 ft/s in order to force all of the gas bubbles down the U-

Tube. This is roughly ten times the velocity of a rising bubble. Due to the lack of field data verifying the stability of smaller minimum velocities required for U-Tube operation, a minimum velocity of 10 ft/s was selected as the design criteria to calculate the minimum water flow rate. This design criteria indicates that the water flow rate increases greatly as the U-Tube diameter increases. In addition, construction costs and constraints also limit the diameter of the U-Tube. In consideration of the above factors, U-Tubes ranging from a 1-foot-radius to a 3-foot-radius (outer casing size) were evaluated. The corresponding flow rates were calculated to be roughly 16 to 141 cfs.

The concentric U-Tube device has an inner and an outer casing as shown in Figure 9.

**Figure 9. Typical Concentric U-Tube with Inner and Outer Casings**




Inner radius values were developed so that area $A_1$ is equal to the area within $A_2$. This ensures that velocities are uniform throughout the U-Tube. This was accomplished by using the relationship:

$$R_1 = R_2 \frac{\sqrt{2}}{2}$$

Where

$R_1$ = radius of inner casing

$R_2$ = radius of outer casing

Gas-to-Water Ratio

Initial model simulations suggest that the gas-to-water flow ratio has a significant impact upon bubble size and oxygen transfer efficiency. Field testing results conducted by Speece (1993) provided sufficient empirical data to calibrate the bubble dynamics for the design model within a range of 2 to 5 percent. The gas-to-water flow ratio therefore remained within a range of 2 to 5 percent to eliminate the potential for gross over or under predictions outside of the calibrated range.

### *Formulation of Alternative Configurations*

U-Tube design alternatives were evaluated using model simulations. Since the design target of 10,000 lbs/d of oxygen is within the model calibration range, alternatives were evaluated over a range of outer U-Tube radii. The corresponding estimates for water and gas flow rates, tube depths, and energy and power requirements are discussed and summarized in the following paragraphs. It should be noted that the values presented in this study are estimates calculated from the design model itself. The system curves are provided to conceptualize the trade-offs between various U-Tube configurations.

Evaluation of DO Concentration vs. Depth within the U-Tube

Figure 10 shows an example of the DO concentrations at varying U-Tube depths. Also shown is the dissolved nitrogen gas concentration. As the nitrogen gas saturation concentration increases with increasing hydraulic pressure, the stripped nitrogen gas re-dissolves into water.

Oxygen transfer capacity and efficiency at different U-Tube depths and three different gas-to-water flow ratios for a 1-foot-radius U-Tube is shown in

Figure 11 and Figure 12. For a 1-foot-radius U-Tube at a gas-to-water flow ratio between 3 and 5 percent and gas flow rates between 28 and 47 scfm, the maximum oxygenation capacity of a single tube is less than 7,000 lbs/d. Therefore, multiple tubes would be required to meet the design capacity of 10,000 lbs/d.

As shown in Figure 10, by increasing the gas-to-water flow ratio, the oxygenation capacity increases, but the transfer efficiency remains nearly constant, as shown in Figure 12. This is because under the operational conditions examined, the oxygen transfer is proportional to the total gas liquid contact area, which is proportional to the gas flow rate.

Similarly, oxygen transfer capacity and efficiency with different tube depths and different gas-to-water flow ratios for a U-Tube with a 1.8-foot-radius is shown in Figure 13 and Figure 14. At this radius, a liquid flow rate of 50.9 cfs is required to meet the design water velocity of 10 ft/s. Two gas-to-water flow ratios were evaluated with a design capacity of 10,000 lbs/d.

**Figure 10. U-Tube Model Results: DO and $N_2$ Concentration at Different U-Tube Depths**

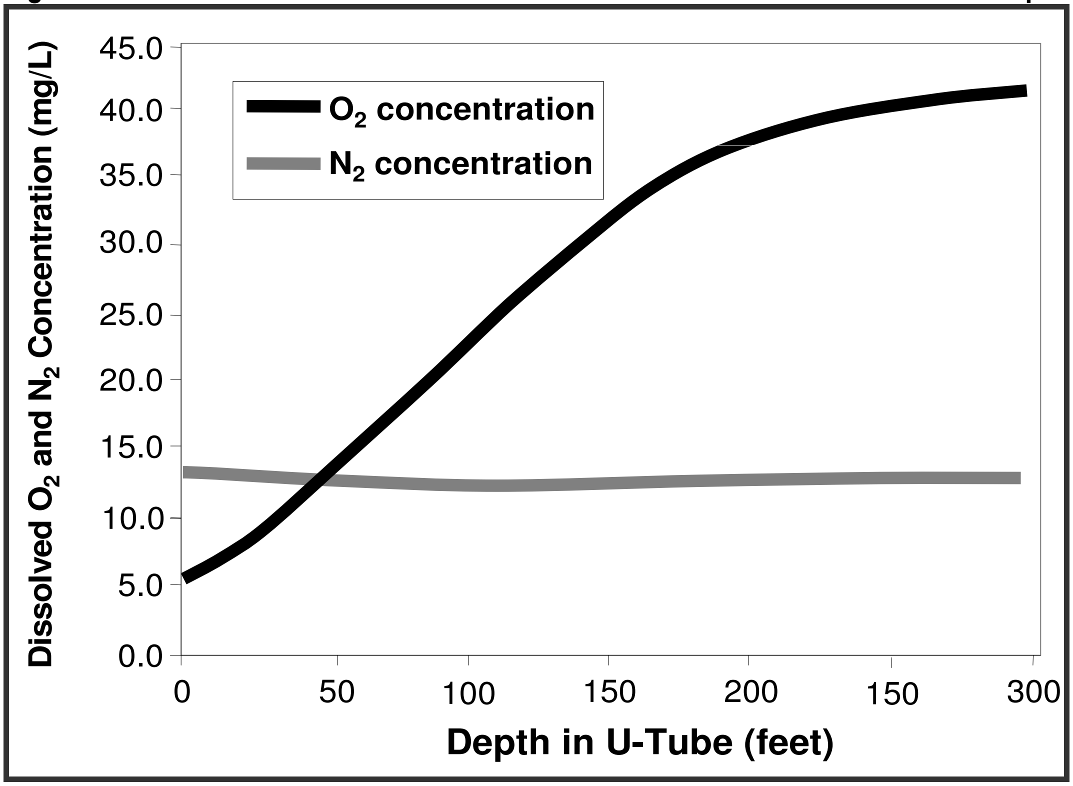



**Figure 11. U-Tube Alternative Evaluation: Oxygen Transfer Capacity vs. Depth**

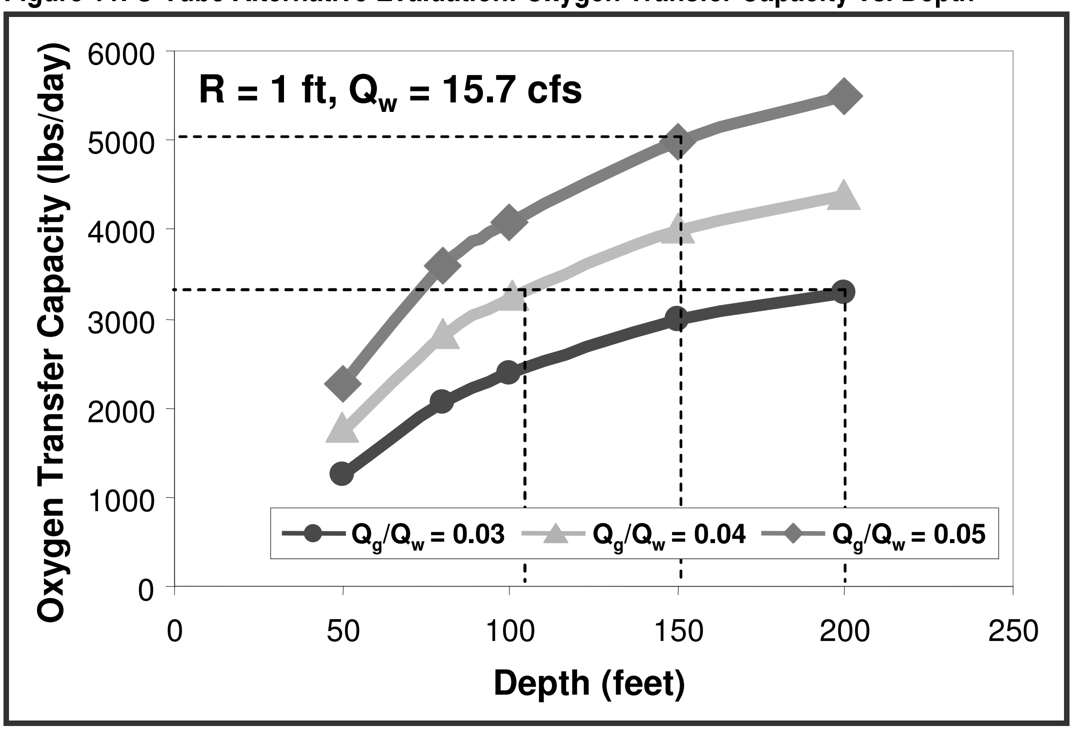


**Figure 12. U-Tube Alternative Evaluation: Oxygen Transfer Efficiency vs. Depth**

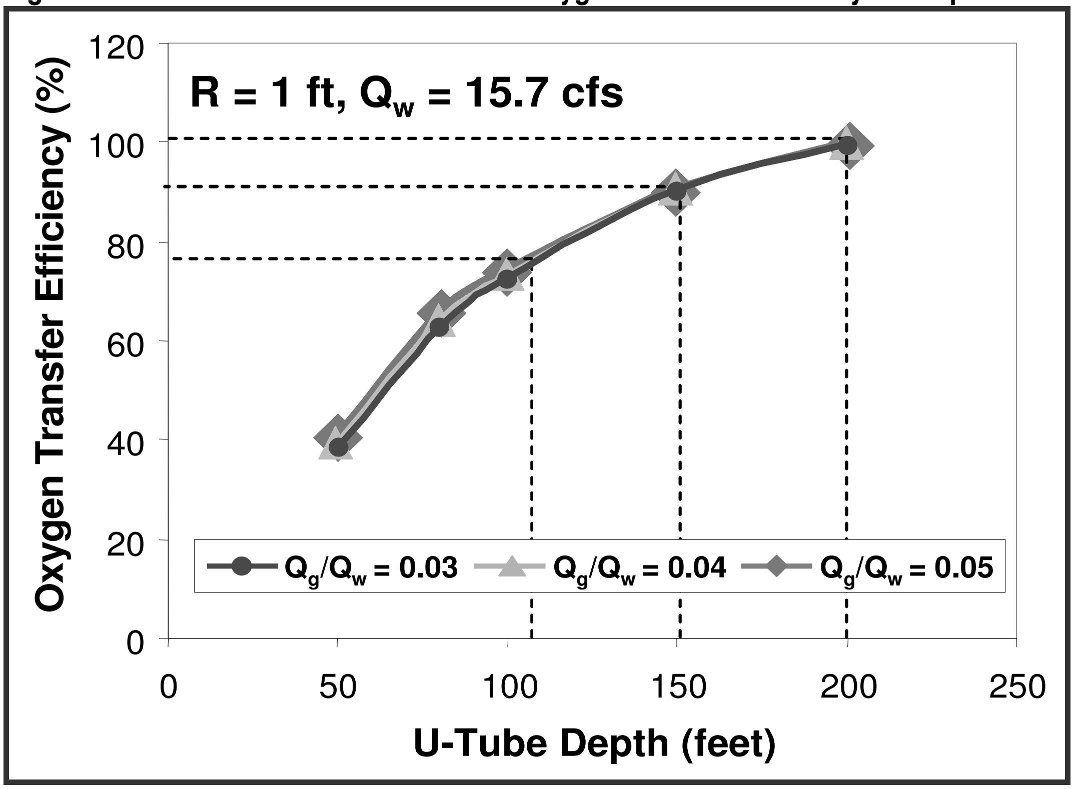



**Figure 13. U-Tube Design Alternative Evaluation: Oxygen Transfer Capacity vs. Depth**

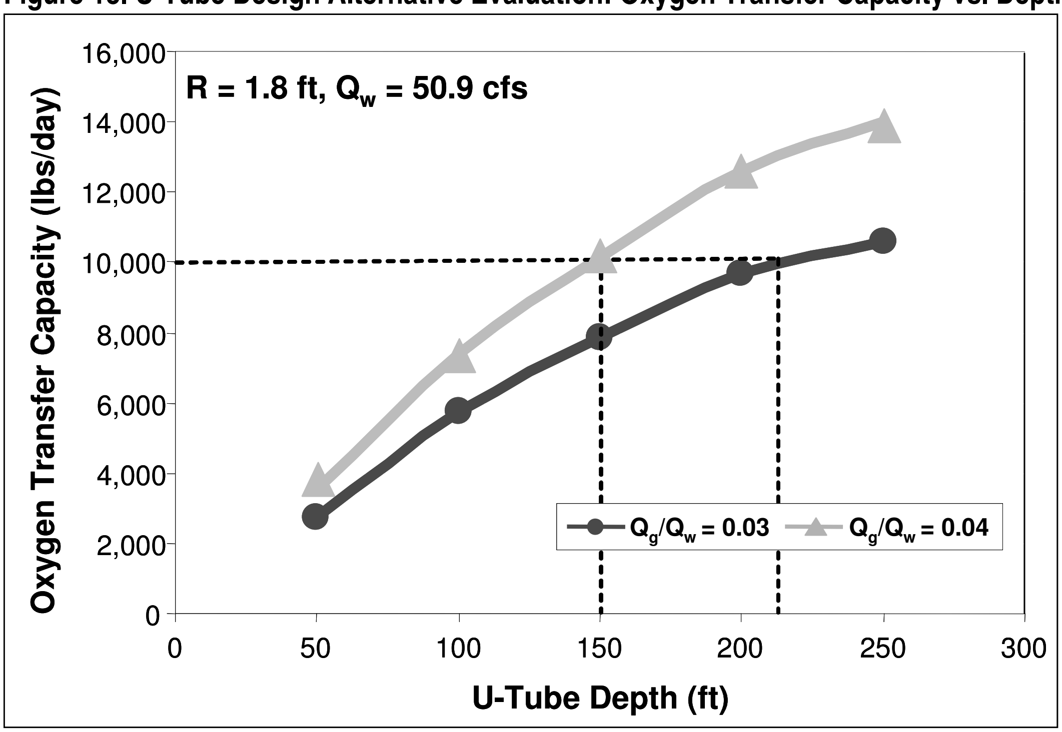
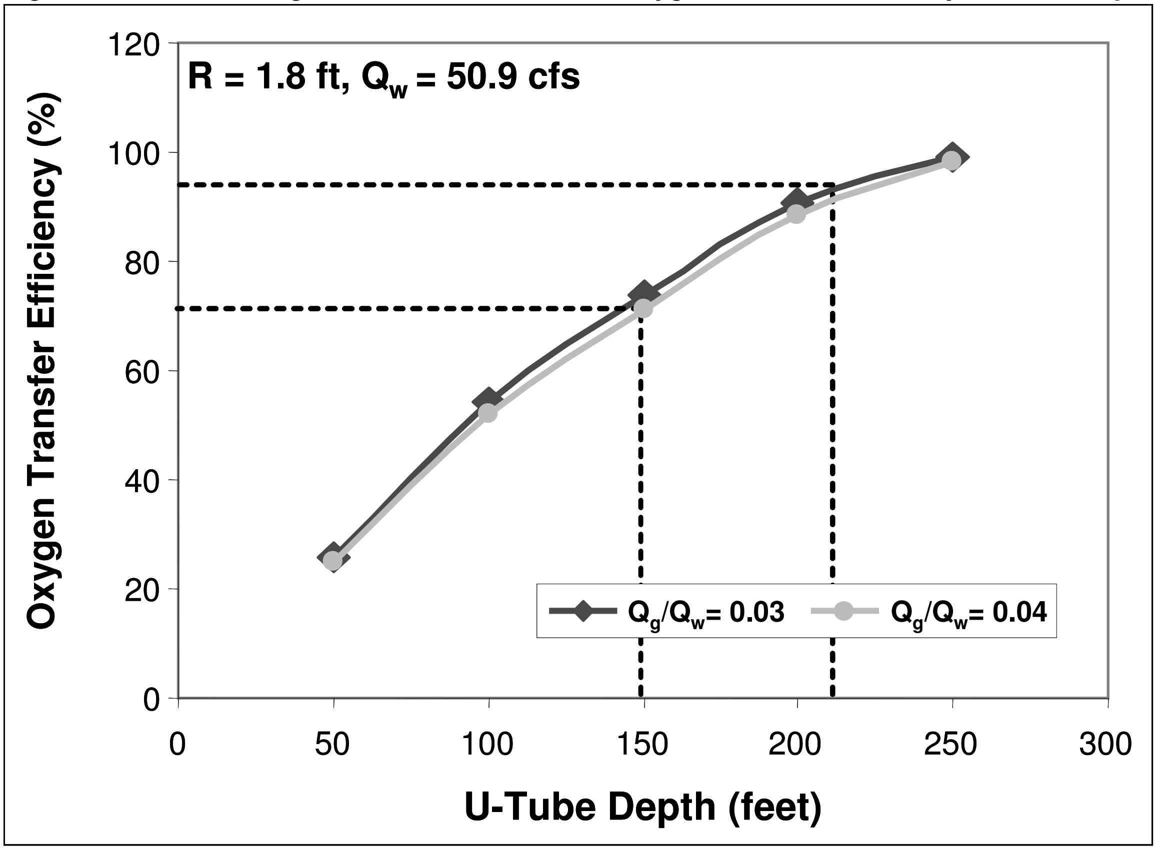


**Figure 14. U-Tube Design Alternative Evaluation: Oxygen Transfer Efficiency vs. Tube Depth**




A single U-Tube with a 1.8-foot-radius is able to deliver 10,000 lbs/d oxygen at a depth greater than 160 feet. The oxygenation capacity increases as the gas supply rate increases. At a gas flow rate of 1.5 cfs (gas-to-water flow ratio of 3 percent), a 1.8-foot-radius and 220-foot depth U-Tube is able to transfer 10,000 lbs/d oxygen at an efficiency of 93 percent. The discharge DO is 41 mg/L. At this tube size and operational condition, the effect of the gas supply rate on oxygen transfer efficiency is still not significant, although more noticeable than the 1-foot-radius U-Tube as described earlier. This implies that more stable and reliable operation is expected for U-Tubes with less than a 1.8-foot-radius. Further, the total oxygenation capacity can be adjusted within a certain range without affecting the transfer efficiency.

Figure 15 and Figure 16 show the total oxygen transfer capacity and efficiency with tubes of different depths and flow rates for a 2-foot-radius U-Tube. As the tube size and gas flow rate increases, the oxygenation capacity of a single U-Tube also increases. At a 2-foot-radius, a single 125-foot depth U-Tube or a 165-foot depth U-Tube is capable of transferring 10,000 lbs/d oxygen from gas to a liquid phase at gas-to-water flow ratios of 4 and 3 percent, respectively. The discharge DO is 33 to 35 mg/L. The transfer efficiency (efficiency of 55 and 73 percent, respectively), however, is significantly lower than the 1.8-foot-radius 220-foot-depth U-Tube.

Figure 15. U-Tube Design Alternative Evaluation: Oxygen Transfer Capacity vs. Depth

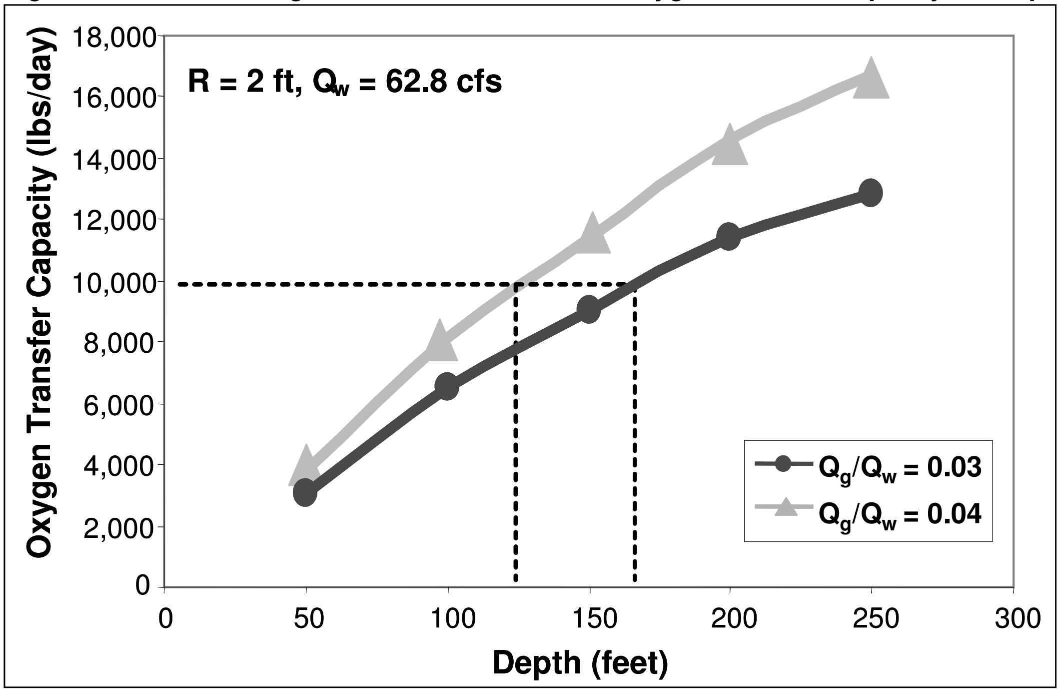
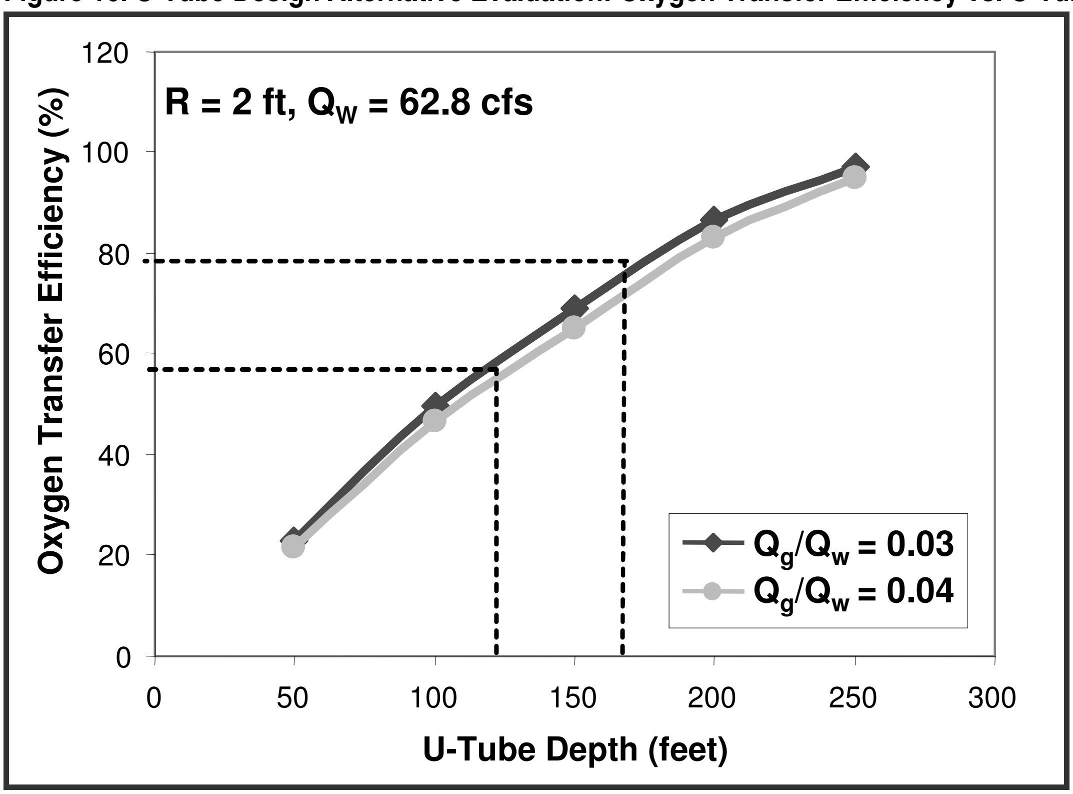



Figure 16. U-Tube Design Alternative Evaluation: Oxygen Transfer Efficiency vs. U-Tube Depth



Because of the higher capacity of a larger sized U-Tube at a similar depth, the shorter contact time at a relatively shallower depth required for 10,000 lbs/d transfer caused lower transfer efficiency.

Increasing the U-Tube size to a 3-foot-radius increased the oxygenation capacity of a single U-Tube significantly. However, oxygen transfer efficiency at the depth needed to transfer 10,000 lbs/d DO is as low as 34 to 52 percent (Figure 17 and Figure 18). A 3-foot-radius, 112-foot depth U-Tube is able to deliver 10,000 lbs/d DO at a water flow rate of 141 cfs and a transfer efficiency of 52 percent.

**Figure 17. U-Tube Design Alternative Evaluation: Oxygen Transfer Capacity vs. Depth**

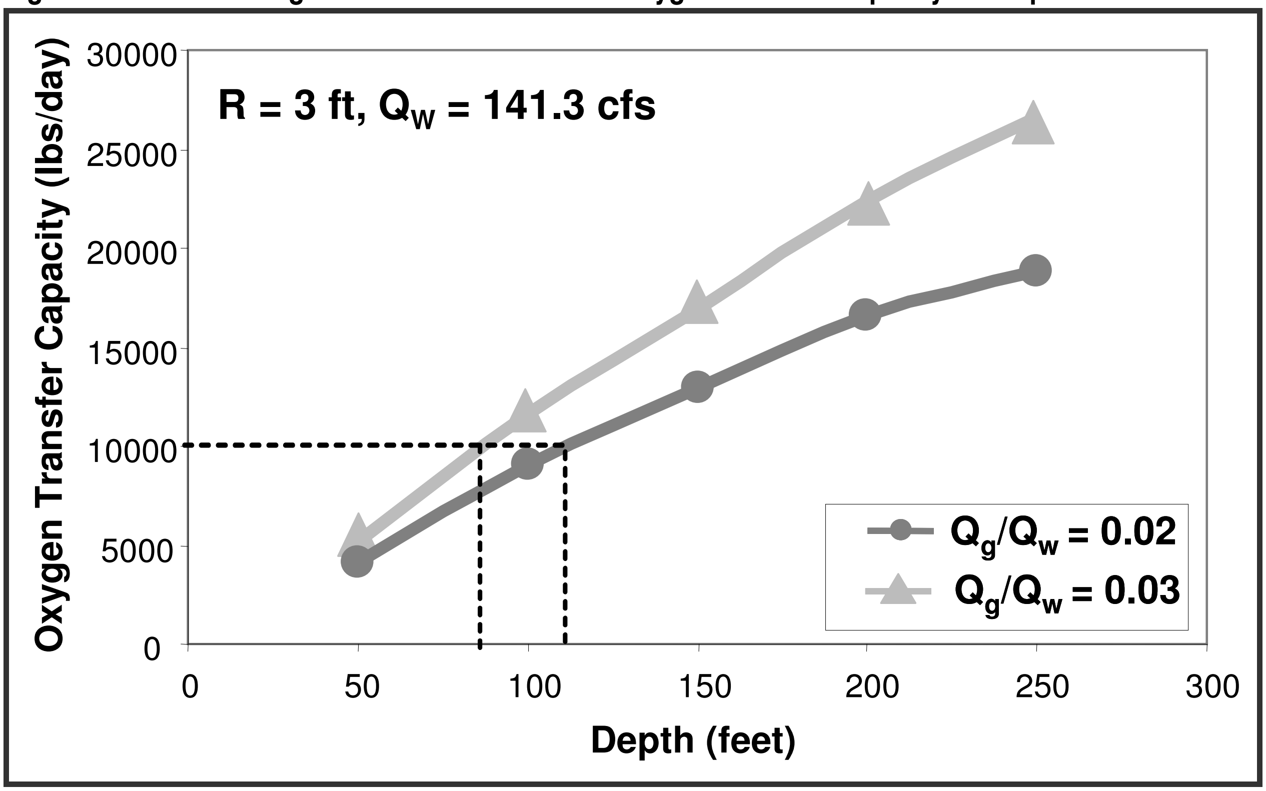
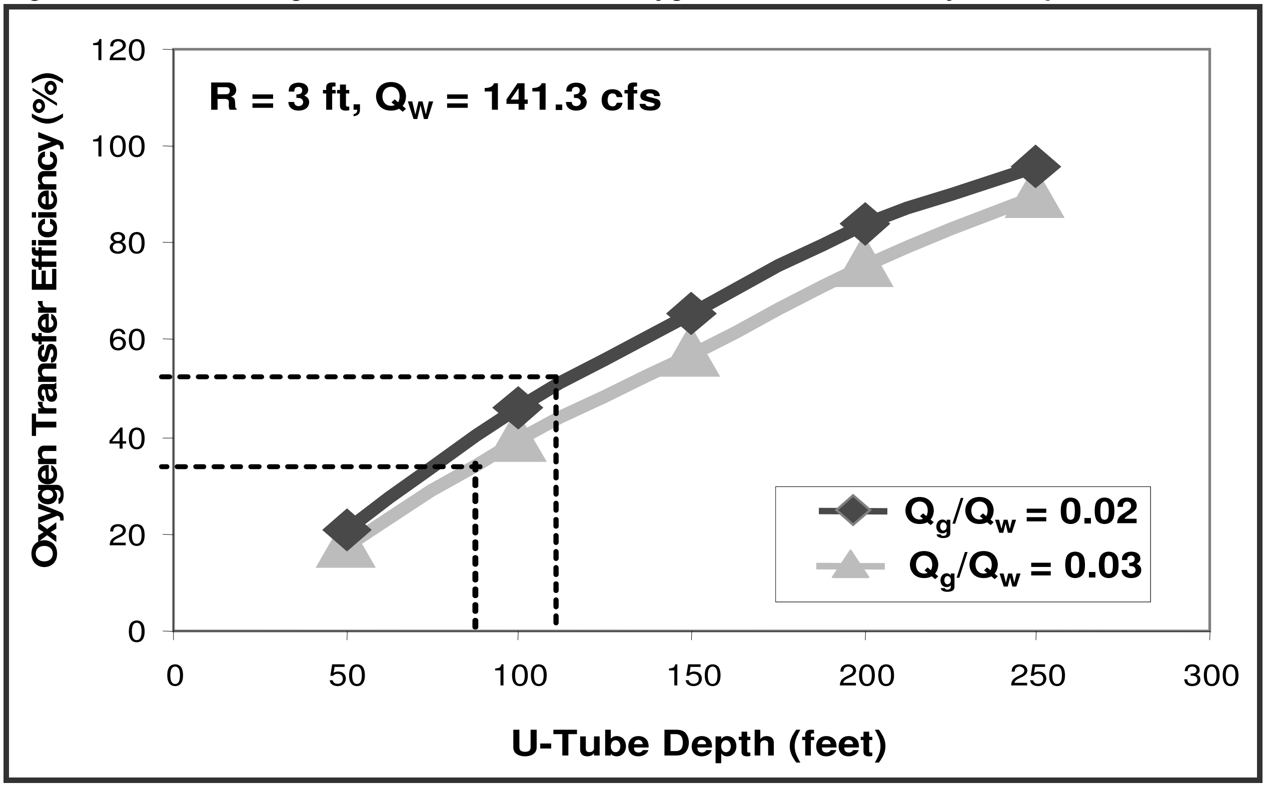


**Figure 18. U-Tube Design Alternative Evaluation: Oxygen Transfer Efficiency vs. Depth**




It should be noted that the above evaluation was only based on model simulations with extrapolation outside the calibrated operational range. The model was only calibrated for a 2-foot-radius U-Tube due to limited available field data. Even though the model is a mechanistic model that allows for performance evaluation at various conditions, factors affecting the basic model assumptions should be considered. For example, the model assumed 100 percent capture of gas by the water flow, and the equivalent initial gas bubble size reflects the extent of completely uniform mixing conditions inside the U-Tube. The hydraulic condition and mixing efficiency for a 2-foot-radius tube, for which the model is calibrated, may not be the same when the U-Tube size is too large or the hydraulic mixing condition of the tube is changed. A pilot study is strongly recommended if the alternative selected is outside of the model calibration range.

## Summary of Evaluation Results

The results of this evaluation, the associated operating conditions, oxygenation performance, and costs are shown in Table 8. The results indicate that for a daily oxygen transfer rate of 10,000 lbs/d, oxygen transfer efficiencies ranging from 52 to 92 percent can be obtained by varying the outer radius from 1 to 3 feet. For each radius, the water flow rate, oxygen supply rate, appropriate gas-to-water flow ratio, depth, and resulting transfer efficiency were calculated

**Table 8. Functionality of Modified U-Tube Configuration Alternatives**

| | | Symbol | Units | A | B | C | D |
|---|---|---|---|---|---|---|---|
| Configuration | No. U-Tubes needed | -- | -- | 2 | 1 | 1 | 1 |
| | Tube outer radius | $R_1$ | ft | 1 | 1.8 | 2 | 3 |
| | Tube height | H | ft | 150 | 220 | 165 | 115 |
| Operational Conditions | Water flow rate | $Q_w$ | cfs | 16 | 51 | 63 | 141 |
| | Oxygen gas flow rate | $Q_g$ | scfm | 50 | 90 | 114 | 168 |
| | Gas-to-water flow rate ratio | $Q_g/Q_w$ | % | 5 | 3 | 3 | 2 |
| | Effective Bubble Size | $R_o$ | ft | .005 | .007 | .008 | .009 |
| | Correction factor | A | ratio | 0.8 | 0.8 | 0.8 | 0.8 |
| | Correction factor | B | ratio | 0.95 | 0.95 | 0.95 | 0.95 |
| | Retention time in tube | T | S | 30 | 42 | 32 | 22 |
| Oxygen Transfer Performance | Initial DO concentration | $C_0$ | mg/L | 5.2 | 5.2 | 5.2 | 5.2 |
| | Discharge DO concentration | $C_e$ | mg/L | 64 | 42 | 34 | 18 |
| | Oxygen transfer efficiency | e | % | 92 | 93 | 73 | 52 |
| | Oxygen transferred/ per tube | $O_2$-trans | lbs/d | 5000 | 10,000 | 10,000 | 10,000 |
| | Total oxygen transferred | | lbs/d | 10,000 | 10,000 | 10,000 | 10,000 |
| | Oxygen feed rate/ per tube | $O_2$-fed | lbs/d | 5,400 | 10,750 | 13,700 | 19,200 |
| | Total oxygen requirement | | lbs/d | 10,800 | 10,750 | 13,700 | 19,200 |
| Power Requirements | | -- | hp | 22 | 36 | 45 | 100 |
| | | | kW | 30 | 48 | 60 | 134 |
| Annual Oxygen Cost (in thousands) | | $ | $US | 75.6 | 75.3 | 95.9 | 134.4 |
| Construction Costs (in millions) | | $ | $US | 1.86 | 2.00 | 2.02 | 2.82 |
| Annual O&M Costs (in thousands) | | $ | $US | 137 | 143 | 163 | 223 |
| Field Data Available | | -- | -- | No | No | Yes | No |

so that 10,000 lbs/d of oxygen was transferred to the receiving water. The rational and discussion of results associated each of the alternative configurations are provided in the following paragraphs.

### *Alternative Configuration A*

Configuration A uses an outer U-Tube radius of 1foot, the smallest of the four alternatives. The corresponding inner piping system radius is approximately 0.7 feet. By applying the down-tube velocity design criteria of 10 ft/s, the corresponding flow rate is 8 cfs. Under these operating conditions, the maximum oxygen transfer capacity is estimated to be 5,500 lbs/d assuming a gas-to-liquid flow ratio of 5 percent (the upper end). Thus, two 1-foot-radius U-Tubes with a depth of 150 feet were configured.  Each is supplied by a small 10 to 15 horsepower pump capable of supplying 8 cfs to each U-Tube. The resulting oxygen transfer capacity is 10,000 lbs/d of oxygen with an oxygen transfer efficiency of 92 percent.

### *Alternative Configuration B*

By increasing the outer U-Tube radius to 1.8 feet, the corresponding flow rate increases from 8 cfs to 50 cfs. Thus, a single 40 horsepower pump is required to meet the down tube velocity criteria. With a depth of 220 feet, this configuration is capable of meeting the 10,000 lbs/d of oxygen transfer requirement at an oxygen transfer efficiency of 93 percent, comparable to that of Configuration A.

### *Alternative Configuration C*

Configuration C represents the U-Tube currently operating on the Tombigbee River (Speece 1993). Field testing suggests that this 2-foot radius U-Tube is capable of transferring 15,000 lbs/d of oxygen at oxygen transfer efficiencies exceeding 90 percent. However, in order to meet the 10,000 lbs/d requirement of this study, Configuration C was modified by shortening the U-Tube from 220 feet to 165 feet. The result was an oxygen transfer capacity of 10,000 lbs/d of oxygen at a lower oxygen transfer capacity of 73 percent. This result indicates that this configuration is suitable for applications requiring greater than 10,000 lbs/d of oxygen if high transfer efficiencies are desired. The corresponding flow rate and horsepower requirements for this alternative are 63 cfs and 45 horsepower respectively. For cost estimating purposes, a pump motor of 50 horsepower was used.

### *Alternative Configuration D*

To examine the capabilities of a much larger U-Tube, Configuration D consists of a U-Tube with an outer radius of 3 feet. The corresponding flow rates and horse power needed to transfer 10,000 lbs/d of oxygen are 141 cfs and 100 horsepower, respectively. With this configuration, the U-tube potential is not fully utilized and the oxygen transfer efficiency drops to 52 percent. As is illustrated with Configuration C, Configuration D would work well for oxygen transfer capacities greater than those required for this study.

## Performance Conclusions

Assuming a 24-hour operating period and an objective oxygen transfer of 10,000 lbs/d, the following conclusions were reached regarding the U-Tube.

1. As transfer efficiencies decrease, oxygen requirements and the associated oxygen supply costs increase. Configuration A displays an oxygen transfer efficiency of 92 percent. As the outer U-Tube radius is increased, transfer efficiencies decrease to 52 percent. Oxygen requirements consequently varied from 10,750 to 19,200 lbs/d. The associated oxygen costs varied from $75,600 to $1.34 million respectively.
2. Holding the gas-to-water flow ratio constant, oxygen transfer capacity increases and oxygen transfer efficiency decreases as the U-Tube outer radii increase. As suggested by comparing Configurations B and C, an outer radius of 1.8 feet (Configuration B) can produce transfer efficiencies of 93 percent with a tube height of 220 feet. However, by increasing the outer radius to 2 feet (Configuration C), the transfer efficiency decreases to 72 percent in order to meet the 10,000 lbs/d oxygen transfer target.
3. Higher transfer efficiencies are obtained with U-Tube outer radii less than 2 feet. For radii larger than 2 feet, transfer efficiencies are less than 90 percent.
4. Water flow rates increase greatly as the U-Tube radius increases, therefore requiring significantly more energy and pumping during operation. For a U-Tube radius range of 1 to 3 feet, the corresponding flow rates were calculated to be roughly 16 to 141 cfs and the horsepower requirements varied from 22 to 100 hp. The 100 hp configuration would require much higher power costs than that of the 22 hp configurations.
5. Oxygen transfer efficiencies increase as gas-to-water ratios decrease, but the oxygen transfer capacity (lbs/d) drops respectively. As the gas-to-water flow ratio increases, oxygen transfer capacity increases, but transfer efficiency decreases rapidly. As oxygen transfer capacity decreases, multiple U-Tubes are needed to achieve the objective of 10,000 lbs/d. The major advantages of using two U-Tubes (i.e., Configuration A) is the ability to easily provide half of the oxygenation capacity when less oxygen is needed or when one unit is out of service for repairs or general maintenance. The disadvantage of using two U-Tubes is the inherent increased maintenance costs of multiple pumping systems.
6. The cost savings incurred from a shorter depth and larger radius U-Tube is offset by an increase in oxygen supply, operation, and construction costs.

In addition to the above conclusions, the assumption that there is uniform mixing in the tube cross section and 100 percent capture of injected oxygen into the U-Tube may not be valid for larger radius tubes. Since there are no field data available to confirm the effect of a larger U-Tube radius (>1 foot) on oxygenation performance, pilot testing is strongly recommended if a larger radius U-Tube is selected as the final alternative. Taller U-Tubes with smaller radii have been proven in the field and are a more reliable alternative.

## Recommended U-Tube Configuration

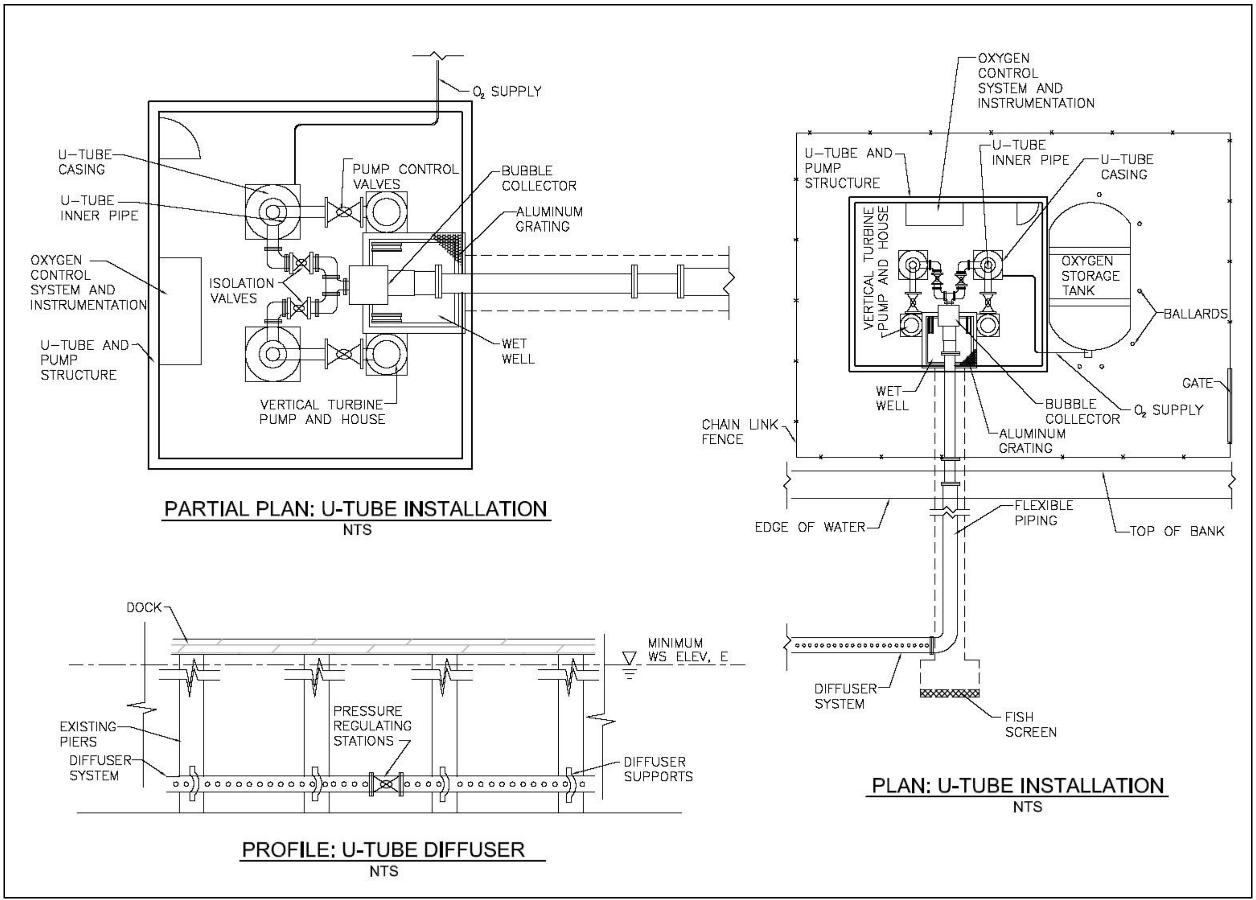
Evaluation and selection of the U-Tube design was based upon the performance data shown in Table 7. All alternatives provide sufficient oxygen transfer capacity to meet the design requirement of 10,000 lbs/d. Total pump power needed for the alternative comprised of two U-Tube units is greater than single U-Tube alternatives because of the minimum velocities required for hydraulic stability. Although the combined target flow rate remains the same, pump horsepower must be sufficient to develop the required internal velocities. As stated above, a major advantage of using two U-Tubes is the ability to easily provide half of the oxygenation capacity when less oxygen is needed or when one unit is out of service for repairs or general maintenance. The disadvantage of using two U-Tubes is increased maintenance costs from having multiple pumping systems. By enlarging the U-Tube outer diameter from 4 to 8 feet oxygen transfer efficiency decreases while the depth required to obtain target oxygen concentrations also decreases. However, the cost savings incurred by using the shorter U-Tubes is offset by increased construction costs. In addition, the relatively lower travel velocity and larger cross-section in the larger-sized U-Tube provides some uncertainty due to the possibility of uneven mixing across the U-Tube section. This may affect oxygen transfer efficiencies. The model assumed uniform mixing under the calibrated conditions and no field data is available to confirm the effect of U-Tube diameter on oxygenation performance. Longer U-Tubes with smaller diameters have been proven in the field and are a more reliable alternative.

Taking this into consideration as well as the six conclusions presented above, the reliability, high oxygen transfer, and low O&M costs of Configuration A would be preferred; therefore, Configuration A was selected for further evaluation.

### *Implementation*

Implementation of Configuration A would provide 10,000 lbs/d of oxygen to the DWSC by pumping approximately 20 cfs of oxygenated water with an estimated DO concentration of 63 mg/L over an operational period of 24-hours. Two 15 hp vertical turbine pumps would be used to extract water from a wet well at a rate of 10 cfs each and deliver it to two 1-foot outer radius, 150-foot-deep U-Tubes. Within the top one-third of each U-Tube, 0.8 cfs of pure oxygen gas would be emitted into the down-tube along with 10 cfs of water. The oxygenated water would then be routed via a 16-inch pipe and discharged to a 24-inch high density polyethylene diffuser lateral where the oxygenated water would be dispersed over a length of 800 feet. Figure 19 provides a conceptual partial plan, plan, and profile for the recommended U-Tube installation.

**Figure 19. U-Tube Installation Plan**




### *Design Elements*

The specific design elements associated with the recommended U-Tube configuration are described in Table 9.

**Table 9. Summary of U-Tube Design Elements**

| Design Element | Description |
|---|---|
| *Site Work* | |
| Foundations and Slabs | Concrete foundations are required for pumping facility housing structure as well as for a 9,000-gallon oxygen supply tank. The foundation for the pumping facility should not exceed 20 x 20 feet. The slab for the 9,000-gallon oxygen storage tank must be at least 20 x 12 feet. An additional 12 x 12-foot slab is required near the oxygen control and refilling equipment. |
| Pavement | Six inches of aggregate base below 3 inches of asphaltic concrete shall provide a clean, orderly, and drivable working area surrounding the pumping and oxygen storage facility. A 50 x 50-foot paved area is required. |
| Fencing | Chain link fencing is used to enclose and secure the pump facility housing and oxygen supply equipment. At least 200 feet of 8-foot-high fencing is required. One 12-foot gate can be installed to allow for entry of personnel and vehicles. |

| Design Element | Description |
|---|---|
| *Structures* | |
| Pumping Facility and U-Tube Housing | A 20 x 20-foot wide split-block masonry building shall be constructed to secure the U-Tube casing, pumping, and electronic control equipment. |
| Wet Well | A wet well connected to the adjacent DWSC can be used to still water prior to extraction by the vertical turbine pumps. The approximate volume of the wet well will vary based upon the final water extraction rate. |
| *General Equipment* | |
| Vertical Turbine Pump, Motor, Casing, and Impeller | Two 15 hp pump motors shall power two vertical turbine pump assemblies. Appropriate casing depth, impeller size, and number of stages should be determined during final design. |
| Fish Screen | One barrel-type fish screen, capable of meeting NOAA Fisheries requirements, with an operation criterion of 20 cfs, can supply water to both pumps. |
| *Mechanical* | |
| Piping | Ductile iron piping with a suitable coating can be used for pump supply and discharge headers. Under the stated design conditions, one 10-inch pipe is expected to supply water from each pump to each U-Tube. A single 16-inch discharge header can be used to transport oxygenated water from the U-Tubes to the diffuser system. |
| Pump Control Valves | Ten-inch pump control valves shall be used to ramp or throttle flows as needed to prevent surge within the piping system. |
| Isolation Valves | Up to three butterfly valves may be placed at key locations to isolate pumping equipment during operation or for maintenance purposes. |
| Pressure Regulating Stations | Pressure regulating stations/valves can be used to equalize pressure within the diffuser system that discharges oxygenated water to the receiving water. These valve stations can be used to ensure equal discharge across the entire diffuser system or to direct oxygenated water to specific areas within the 800-foot reach of diffuser piping. Regulating stations are controlled by the electronic control equipment and programming located with the pump facility housing. They can be controlled via radio transmission or by wire feed. |
| *Oxygen Supply* | |
| Oxygen Storage Tank | A 9,000-gallon storage tank shall be provided and installed by a commercial oxygen supplier. Oxygen storage equipment is available on a monthly rental basis. |
| Oxygen Control and Supply Equipment | Electronic instrumentation and an oxygen gas control valve shall be used to measure and control oxygen supply rates to the system. |
| *Special Construction* | |
| Outer U-Tube Casing | For permanent construction, it is recommended that a welded steel casing, 2 feet in diameter and at least 150 feet in height be installed vertically into the ground. Specifications and exact thickness of the welded steel piping structure can be finalized during the final design phase. For the purposes of cost development a thickness of 1-inch was used as a conservative estimate. |
| Inner Piping System | An 8-inch pipe system, approximately 145 to 149 feet long, shall be developed and installed in the center of the 2-foot U-Tube casing. The appropriate support system, configuration, and other considerations shall be developed during final design. |

| Design Element | Description |
| --- | --- |
| Diffuser Lateral | A single 24-inch liquid diffuser lateral approximately 800 feet long and constructed of high density polyethylene pipe shall be used to transport and disburse oxygenated water to the receiving water. Orifice sizes shall be designed such that the head loss through the orifices is 10 times that of the head loss through the pipe. Orifice spacing and size shall be considered during final design. Underwater construction and installation activities are required. |

### *Design Considerations*

The following paragraphs present additional key design considerations to be evaluated during field testing and final design of the U-Tube system.

Down-Tube Velocity

Dr. R.E. Speece recommends that a down-tube velocity of 10 ft/s be used as an operational criterion for stable U-Tube performance (Speece 1993). Contrary to this recommendation, field testing data obtained by Dr. Speece suggest that at lower down-tube velocities, it is possible to obtain higher oxygen transfer efficiencies. This is possible due to the inherent increase in residence time (or oxygen gas/receiving water contact time) due to lower velocities over the same depth pipe. If the travel velocity is decreased, the time it takes to travel the same distance increases. Thus, a longer residence time and increased oxygen transfer rate may be observed. Using lower down-tube velocities may have a direct impact on the U-Tube system by decreasing capital and annual O&M costs.

However, it was also observed by Dr. Speece that at down-tube velocities below 10 ft/s oxygen transfer performance was unstable. Due to this unexplained instability, Dr. Speece suggests that lower down-tube velocities be avoided.

For the purposes of this study, the recommended down-tube velocity of 10 ft/s was used as a design criterion. It is recommended that this parameter be evaluated in further detail by conducting field testing activities and by obtaining additional empirical data either supporting or disputing Dr. Speece's recommendations before final design.

Effective Bubble Size and Gas-to-Liquid Flow Ratio

During the development of the various U-Tube alternative configurations, the effective bubble size was calculated for each operational condition. It is assumed that for each different operational condition (i.e., a specific gas flow rate, water flow rate, and U-Tube depth) the effective bubble size would change due to the varying hydraulic conditions within the U-Tube and especially at the location where oxygen gas is emitted into the down-tube. This variance in hydraulic forces causes bubbles to coalesce or break apart depending on the internal U-Tube dynamics. As described previously, this dynamic was examined with the use of a calibrated computer model developed for this study. Although, the model estimates represent real world conditions based upon empirical field results, using this assumption within the design process complicates the meaning of the results.

In order to simplify the design process, it is possible to assume a fixed initial bubble size. This may be achieved by installing fine bubble diffusers that produce a known bubble size into the U-Tube rather than a gas nozzle with a single orifice. The use of a fine-bubble diffuser would ensure that the initial bubble size would meet a specific size requirement at the discharge point. As the gas and liquid mixture travels through the U-Tube system, the bubble sizes would decrease due to the increase in hydrostatic pressure and the mass transfer of oxygen to the water. Thus, since system performance improves with smaller bubble sizes, the use of a fixed initial bubble size during performance calculations would provide a conservative estimate while the actual system performance would be better than the calculated estimate.

This assumption would simplify the design process by eliminating a variable from the model and would provide more intuitive conservative results.

#### *Further Recommendations*

Both the down-tube velocity and the initial bubble size affect oxygen transfer and U-Tube performance greatly. It is recommended that a scaled U-Tube field test be conducted in order to further knowledge of these two parameters with regard to how these parameters affect system performance.

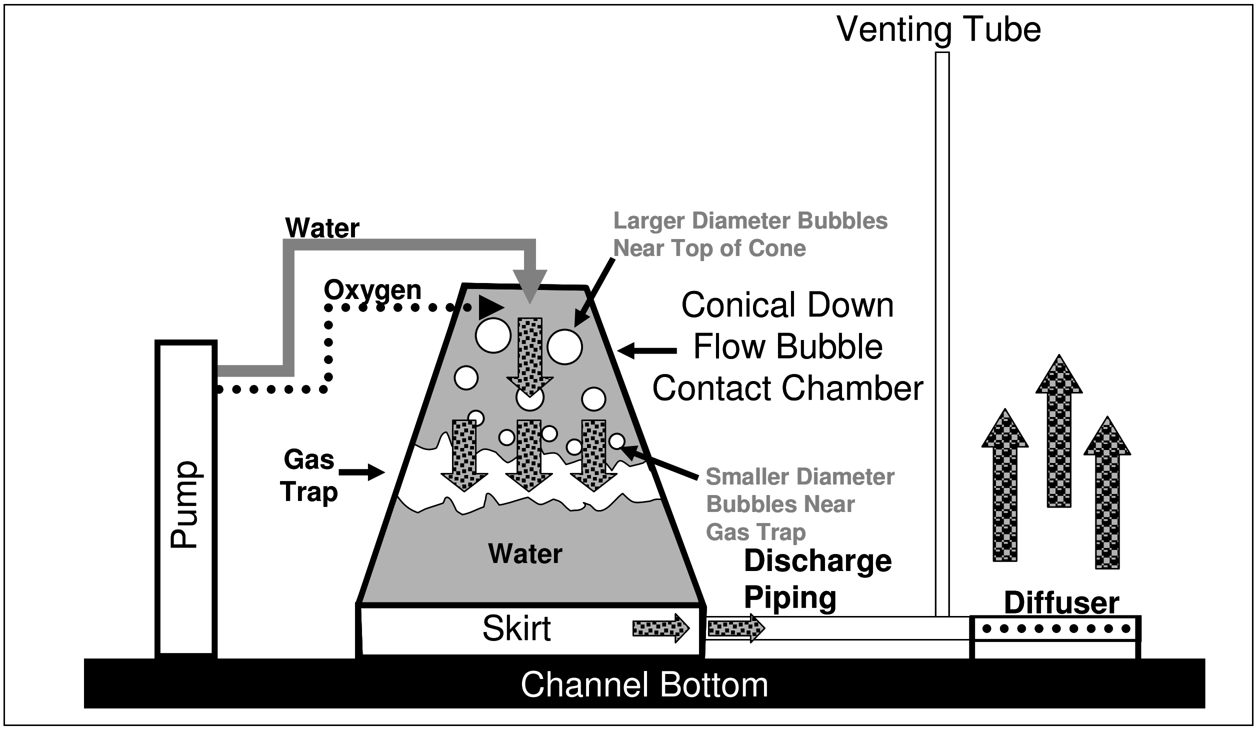
## SPEECE CONE

### Technology Overview

#### *Configuration Description*

The Speece Cone assembly generally consists of an oxygen source pumped from an onshore supply facility, conical down flow bubble contact chamber with a skirt, a submersible water pump, and a venting system made up of discharge piping and a gas venting tube. For the purposes of this study, the discharge piping is assumed to be connected to diffuser piping, which creates smaller bubbles that facilitate larger oxygen transfer efficiency (Figure 20). During operation, the Speece Cone is typically placed at the bottom of a waterbody to take advantage of the water pressures which increase as depth increases (referred to as hydrostatic pressure). Oxygen gas is delivered to the top of the Speece Cone from an onshore supply facility via separate distribution lines. Water is oxygenated as the mixture travels through the cone and is discharged via the discharge system attached to the skirt of the cone.

**Figure 20. Typical Speece Cone Assembly Configuration**



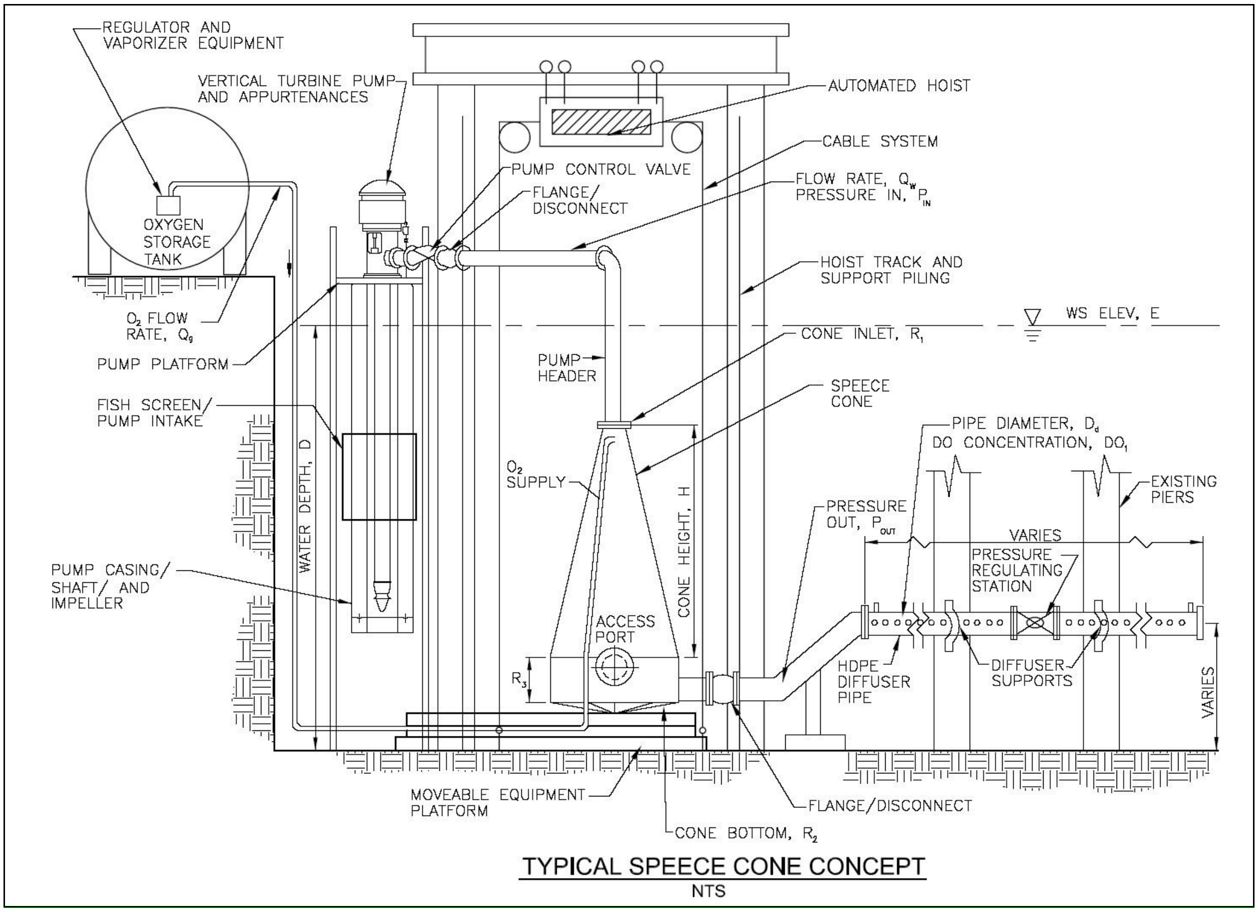

## *System Components*

Speece Cone DO aeration systems usually consist of the Speece Cone assembly, an onshore oxygen supply facility, and a hoist that can raise the Speece Cone assembly from the water when the system is not in operation or for routine maintenance (see Figure 21).

Water and oxygen gas are introduced simultaneously from the top of the cone. The water and oxygen mixture travels towards the bottom of the cone. As the mixture travels downward, the travel velocity decreases as the cone cross-sectional area increases. This decrease in travel velocity increases the contact time of the water with oxygen gas. Near the top of the cone, the downward velocity of the water into the cone must be sufficient to overcome the natural upward buoyancy velocity of the bubbles. Speece Cones are designed so that there is equilibrium between the downward velocity of water and the upward buoyancy velocity of bubbles. This equilibrium creates a layer of oxygen gas in the cone (gas trap). As water is pushed from the top of the cone to the skirt, it passes through this gas trap and becomes saturated with oxygen. This saturated water is then immediately discharged through the discharge piping and diffuser system into the surrounding water.

The position and size of the gas trap can be adjusted by modifying the gas-to-liquid flow ratio, water flow rates, and/or by increasing pressures within the Speece Cone.

**Figure 21. Typical Speece Cone System**




Increased pressures within the Speece Cone enhance transfer efficiency. Pressures may be increased by mechanical means (i.e., via larger water pumping equipment, forcing water into the Speece Cone via pumping facility) or by positioning the Speece Cone at deeper locations to take advantage of increased hydrostatic pressures. Due to the depth of the DWSC, the Speece Cone can only be installed at depths of 25 to 30 feet.

### *Oxygen Transfer*

Oxygen transfer performance of Speece Cones is sensitive to water flow rates, gas-to-water flow rate ratios, and Speece Cone dimensions. Speece Cones enhance oxygen transfer efficiencies by subjecting the oxygen and water mixture within the cone to pressures greater than those above the water surface, resulting from either hydrostatic pressures of water above the cone or by water being mechanically forced into the cone. When in operation, Speece Cones have exhibited oxygen transfer efficiencies between 70 and 99 percent, and effluent DO concentrations of up to 50 mg/L (Speece 1996).

### *General Performance*

The summary of general performance expectations of a Speece Cone aeration system are summarized in Table 10.

**Table 10. General Performance Expectations of Speece Cones**

| Function | Performance Description |
|---|---|
| Discharge DO Concentrations | Up to 50 mg/L DO with water temperatures up to 82.4 °F. |
| Oxygen Transfer Efficiency | 70% to 99% oxygen can be dissolved into water. |
| Energy Consumption | Energy consumption is dependant upon the presence of hydrostatic pressure due to the water depth above the Speece Cone and oxygenation goals. The use of pumping systems to increase internal Speece Cone pressures will require additional energy consumption when using the Speece Cone in relatively shallow waterbodies such as the DWSC. |
| Oxygen Transfer Driving Force | Pressures with the Speece Cone may be developed so that the driving force of oxygen being transferred into the water is higher. This occurs because as pressures increase, the DO saturation concentration increases and therefore increases the DO deficit. |
| Nitrogen Stripping | The high hydrostatic pressure also increases saturated nitrogen concentration, therefore minimizing nitrogen stripping. |

## Evaluation of Modified Speece Cone Configurations

### *Oxygen Transfer Model Development*

For this study, a model was developed to predict the oxygen bubble dynamics and oxygen transfer in a Speece Cone. The model is based on differential equations that govern the mass balance of both gas and water at different depths within the Speece cone, configurations, and dimension of the Speece Cone. Most differential equations were adopted from the model developed for Speece Cone by McGinnis et al (1998) with some modifications and addition of equations by HDR. The design model simulates oxygen transfer, nitrogen stripping and DO concentrations at any depth in a Speece Cone. Oxygen transfer efficiency is calculated as a function of initial bubble size, gas and water flow rates, depth of operation and dimensions of the Speece Cone. The parameters used in the model, their definition and units used are listed in Table 11.

The following equations describe the change in molar flow rate of gaseous oxygen and nitrogen in the undissolved phase, as well as the changes in molar flow rate of dissolved oxygen and nitrogen gases at any given depth. The set of differential equations used to develop the design model was solved simultaneously using Euler's method. The constants provide the operational conditions, parameters and cone dimensions. The calculated inputs include all parameters that are determined based on the operational conditions given. The correlations and mass balance equations used for model development follow.

**Table 11. Variables and Parameters Used in the Speece Cone Model.**

| Variable | Description | Unit |
|---|---|---|
| $R_1$ | Radius of the top of the cone | ft |
| $R_2$ | Radius of the bottom of the cone | ft |
| h | Height of cone body | ft |
| hs | Height of the skirt at the bottom of the cone | ft |
| ht | Total height of the cone including cone body and skirt | ft |
| $Q_g$ | Gas flow rate | scfm |
| $Q_w$ | Water flow rate | cfs |
| $V_z$ | Water flow velocity in relation to cone at depth z | ft/s |
| $V_s$ | Superficial water flow velocity with gas mixture at depth z | ft/s |
| $V_b$ | Gas bubble travel velocity in relation to cone | ft/s |
| $\varepsilon_g$ | Fraction of gas per unit volume of water and gas mixture | fraction |
| r | Gas bubble radius size | ft |
| $c_i$ | Gas molar concentration in gaseous phase | mole/L |
| $C_i$ | Dissolved molar gas concentration | mole/L |
| $P_i$ | Partial gas pressure | psi |
| J | Mass transfer flux across surface | mole/m$^2$-s |
| $K_{OL}$ and $K_N$ | Mass transfer coefficient for oxygen and nitrogen gases | ft/s |
| m | Molar flow rate of undissolved gas | mole/s |
| M | Molar flow rate of dissolved gas | mole/s |
| $H_O$ and $H_N$ | Henry's Constant for oxygen and nitrogen gas | mole/m$^3$-Pa |
| α | Correction factor for the effect of impurities in water on mass transfer coefficient | ratio |
| β | Correction factor for the effect of impurities in water on the saturated DO concentration | ratio |

$$V_s = \frac{Q_w}{\pi \times \left[ \left( \frac{R_2 - R_1}{h} \right) \times z + R_1 \right]^2} \quad (1)$$

$$V = \frac{V_s}{1 - \varepsilon_g} \quad (2)$$

$$\varepsilon_g = \frac{\Sigma C_i \times R \times T}{P_z} \quad (3)$$

$$\varepsilon_{g(0)} = \frac{Q_g}{\pi \times R_0^{\ 2} \times (V + V_b)} \quad (4)$$

$$dt = \frac{dZ}{(V + V_b)} \quad (5)$$

$$J = \alpha \times K_{OL} \times (\beta \times H \times P_i - C) \quad (6)$$

$$\frac{dM}{dZ} = \alpha \times K_{OL} \times (\beta \times H \times P_i - C) \times \frac{4\pi \times r^2 \times N}{(V + V_b) \times (1 - \varepsilon_{g(z)})} \quad (7)$$

$$N = \frac{Q_g}{\frac{4}{3} \times \pi \times r_0{}^3} \quad (8)$$

$$M = \pi \times R^2 \times V \times C \quad (9)$$

$$C_z = \frac{M}{\pi \times R_z{}^2 \times V_z} \quad (10)$$

$$\frac{dm}{dZ} = -\alpha \times K_{OL} \times (\beta \times H \times P_i - C) \times \frac{4\pi \times r^2 \times N}{(V + V_b)} \quad (11)$$

$$m = \pi \times R^2 \times (V + V_b) \times c \quad (12)$$

$$c_z = \frac{m}{\pi \times R_z{}^2 \times (V + V_b)_z} \quad (13)$$

$$\frac{r}{ro} = \left(\frac{m_{O2} + m_{N2}}{m_{O2(0)} + m_{N2(0)}}\right)^{\frac{1}{3}} \quad (14)$$

if r <7 x $10^{-4}$ m

$$V_b = 4474 \times r^{1.357} \quad (15)$$

if 7 x$10^{-4}$ < r <5.1x $10^{-3}$ m

$$V_b = 0.23 \quad (16)$$

if r >5.1 x$10^{-3}$ m

$$V_b = 4474 \times r^{1.357} \quad (17)$$

$$H_O = 2.125 \times 10^{-3} - 5.021 \times 10^{-7} \times T + 5.77 \times 10^{-9} \times T^2 \quad (18)$$

$$H_N = 1.042 \times 10^{-5} - 2.450 \times 10^{-7} \times T + 3.171 \times 10^{-9} \times T^2 \quad (19)$$

$$K_{OL} = 0.6 \times r \quad (20)$$

if r < 6.67 x$10^{-4}$ m

if r > 6.67 x$10^{-4}$ m

$$K_{OL} = 4 \times 10^{-4} \quad (21)$$

### *Model Calibration and Validation*

The design model developed to evaluate oxygen transfer within the Speece Cone was calibrated with full-scale field data made available from a Speece Cone installation at the Logan Martin Dam for the Alabama Power Company by Speece in 1990. The Speece Cone configuration, operational conditions and field data are summarized in literature prepared by Dr. R.E. Speece in 1990. The Speece Cone oxygenation performance was evaluated at different water flow rates between 15 and 105 cfs, and for a range of oxygen gas-to-water flow rates between 3 and 5 percent. Key operational indictors included water flow rate, oxygen feed rate, discharge DO, head loss in the cone and oxygen transfer efficiency. Field tests were also conducted for different oxygen injection points and with the bubble harvester venting "on" and "off". The different oxygen injection points included direct injection into the cone versus using a siphon-type system. The pressure drop in the system was evaluated under different conditions:

- With no oxygen injection,
- With no water flow through the cone, and
- With a water flow rate from 22 to 25 cfs.

The total head-loss through the cone was found to be nearly constant: 6 feet at the flow conditions tested. The system configuration parameters of the Speece Cone installed at Logan Martin Dam are shown in Table 12.

**Table 12. Configuration Parameters of Speece Cone at Logan Martin Dam for Model Calibration**

| | Symbol | Value | Unit |
|---|---|---|---|
| Temperature | T | 82.4 | °F |
| Elevation of water surface | E | 0 | ft |
| Operation depth-inlet | D | 35 | ft |
| Cone top radius | $R_1$ | 0.83 | ft |
| Cone bottom radius | $R_2$ | 4.5 | ft |
| Cone height | h | 15 | ft |
| Water flow rate | $Q_w$ | 15 to 35 | cfs |
| Gas-to-water flow rate | $Q_g/Q_w$ | 3, 4, and 5 | % |
| Oxygen percentage in gas | $f_{O2}$ | 100 | % |
| Initial oxygen concentration in water | $C_o$ | 2.0 | mg/L |
| Correction coefficient for saturated DO | α | 0.95 | ratio |
| Correction coefficient for transfer rate | β | 0.8 | ratio |

The correlation of model simulation results to the field data are shown in Figure 22 and Figure 23.

**Figure 22. Speece Cone Model Calibration: Oxygen Transfer Efficiency vs. Oxygen Feed Rate**

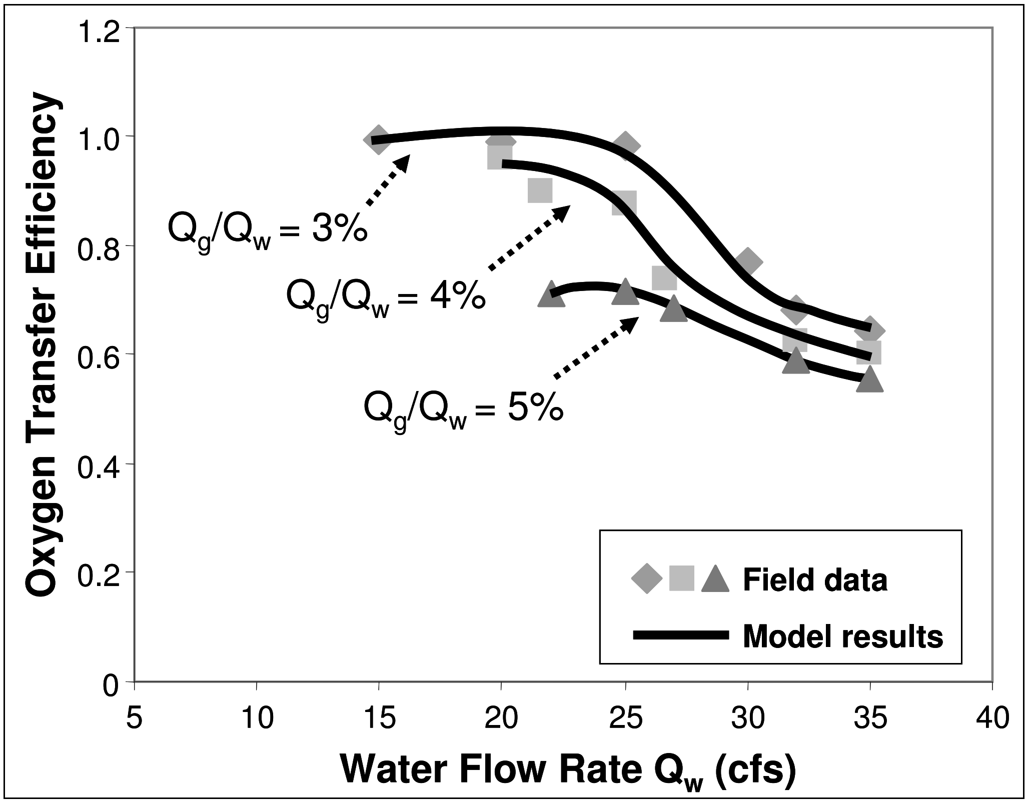
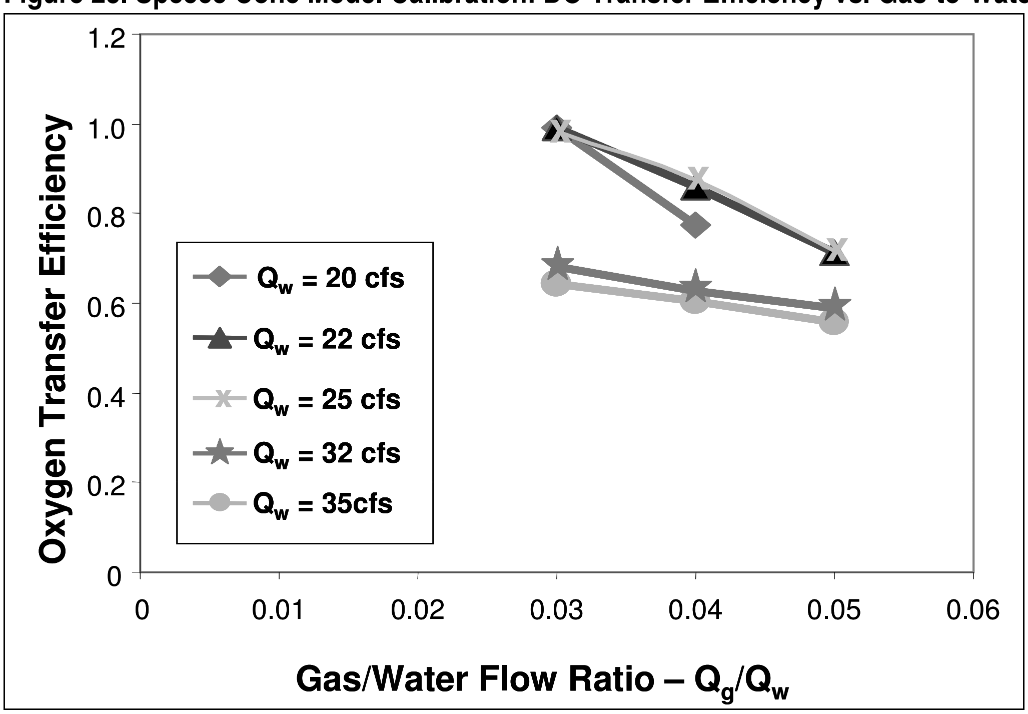



**Figure 23. Speece Cone Model Calibration: DO Transfer Efficiency vs. Gas-to-Water Flow Ratio**



The model was calibrated to best correlate with the field data by changing the equivalent initial gas bubble size using the configuration shown in Table 12. The oxygen transfer efficiency is greatly affected by the initial gas bubble size, which is determined by the diffuser size and type, gas and water flow rates, and the gas and liquid hydraulic mixing efficiency. The correlation of the model simulation results to the field-measured data demonstrates that the model is able to simulate the oxygenation performance of Speece Cone at the given operational conditions. The calibration of the model allowed development of initial bubble size as a function of water flow rate and gas supply ratio. The design model used the following assumptions to simplify the calculations.

- All gas bubbles were assumed to have equal size and no bubble collapses were assumed to occur.
- Oxygen injected was assumed to be 100 percent captured by the water flow.
- Oxygen transfer was uniform at a given cone depth.

It should be noted that these assumptions may not apply in real applications. However, the calibration of the design model to empirical field data uses the equivalent initial gas bubble size as a parameter to account for deviations from ideal conditions, and to account for other factors that may affect the device performance, but are not directly included in the model equations. The fact that the model is able to simulate the overall oxygen transfer performance and closely match the field data supports the above assumption, approach, and use of the model for design evaluation.

Figure 24 presents the calibrated model results that demonstrate accurate estimation of initial bubble size given the oxygen gas flow rate and liquid flow rate within a range of 3 to 5 percent gas-to-liquid ratio. These results were used to evaluate internal hydraulic dynamics its affect on bubble size throughout the Speece Cone evaluation.

### *Basic Assumptions and Design Criteria*

Design criteria for Speece Cone aeration devices are based upon results from background research, understanding of the technology mechanisms, preliminary model development, and model sensitivity studies conducted for this oxygen aeration technology. The design criteria and conditions for Speece Cone are summarized in Table 13. The rationale for use and sources of the selected design condition are described in the following paragraphs.

#### Operating Pressure

For the purposes of this evaluation two operating pressures were evaluated: the natural pressure subjected to the Speece Cone due to hydrostatic forces of the water column above the Speece Cone (approximately 15 feet of hydraulic head) and a pressurized condition subjecting the Speece Cone to 35 feet of hydraulic head. Water depth and the associated hydrostatic pressure were measured at the cone base to the mean water surface elevation of the DWSC.

**Figure 24. Speece Cone Model Calibration: Equivalent Initial Gas Bubble Size vs. Oxygen Gas Flow Rate and Water Flow Rate**

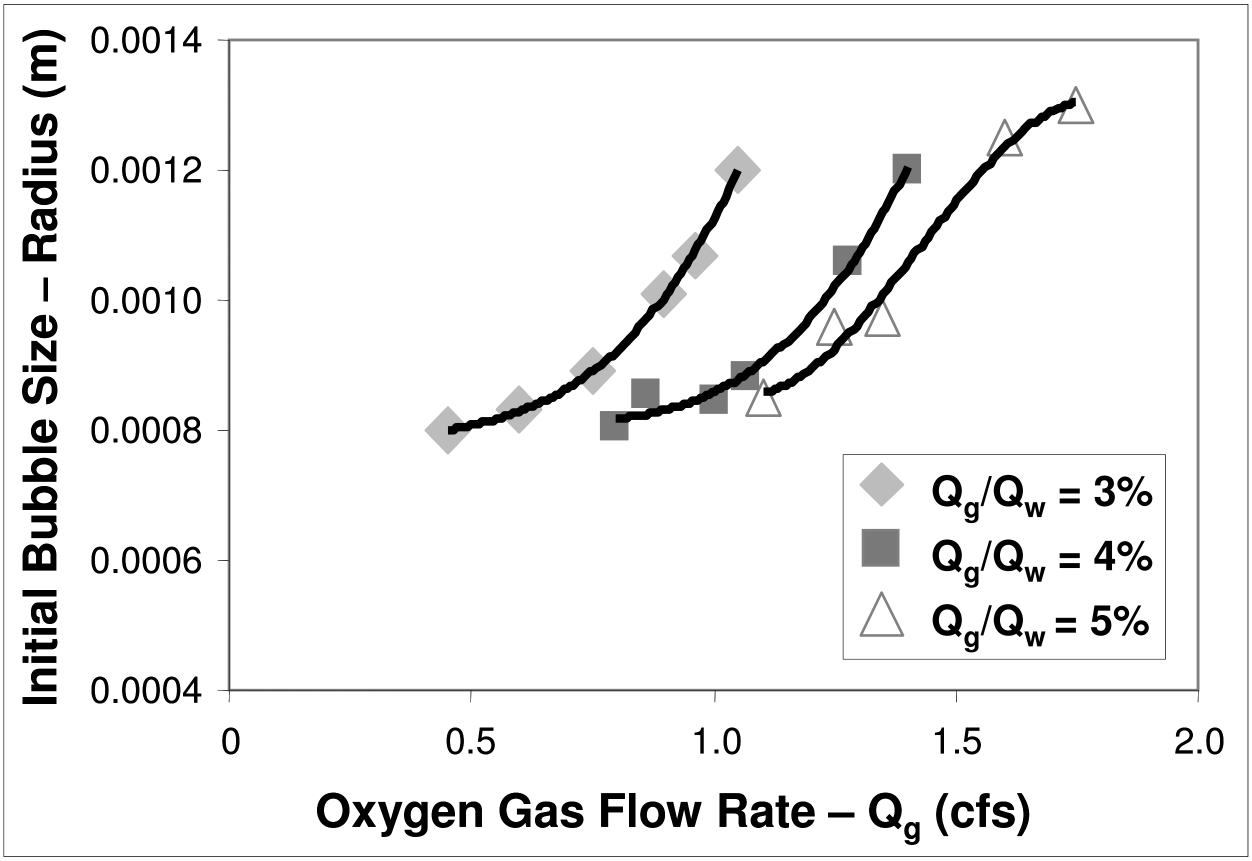



**Table 13. Preliminary Design Criteria and Conditions for Speece Cone**

| Description | Symbol | Unit | Design Range |
|---|---|---|---|
| **Device Configuration** | | | |
| Water depth at cone base | H | ft | 35 |
| Cone top (inlet) diameter | $D_1$ | ft | 0.83 to 2 |
| Cone side wall slope | tan | θ | 0.25 to 0.26 |
| Cone bottom skirt height | $R_3$ | ft | 5 |
| Cone height | H | ft | 15 to 30 |
| **Operational Conditions** | | | |
| Water flow rate | Qw | cfs | 15 to 35 |
| Gas-to-water flow ratio | $Q_g/Q_w$ | % | 2 to 4 |

<u>Top Inlet Radius</u>

Variations in the radius of the top inlet were shown to have minimal impact on the cone performance by Speece (1993) as well as the model simulations for this Engineering Feasibility

Study. Therefore, the top cone inlet was fixed to be in the same range as the Speece Cone installed at Martin Logan Dam. Thus, for this study, inlet radii of 0.83 and 1.8 feet were evaluated.

Cone Side-Slope

Model simulations indicate that the cone side-wall slope has a significant effect on cone oxygen transfer performance and efficiency. The optimal slope, expressed as tan θ (the angle of side-wall relevant to vertical axile), is from 0.25 to 0.26. As the slope decreases, the Speece Cone begins to act much like the U-Tube where depth begins to play a major role in oxygen transfer efficiency.

Cone Height

The cone height of the Speece Cone at Martin Logan Dam is 15 feet. During evaluation of the Speece Cone design model, the cone height was evaluated from 15 to 30 feet and assumed that similar hydraulic conditions could be maintained (i.e. successful entrainment of gas bubbles could be maintained). Validation of these assumptions is highly recommended through a pilot study if the final selected alternative is outside of the calibrated range of operation. The cone bottom skirt was fixed at 5 feet to facilitate the outlet piping.

Water Flow Rates

Water flow rates ranging from 20 to 150 cfs were chosen for two primary reasons. First, preliminary model simulations show that as water flow rates decrease below 15 cfs or increase beyond 35 cfs, the oxygen transfer efficiency begins to diminish. Second, these flow rates are sufficient to meet the 10 ft/s design velocity needed to entrain all of the gas bubbles emitted into the Speece Cone.

Gas-to-Water Flow Ratio

The gas-to-water flow ratio was selected to be between 2 and 4 percent. At a ratio lower then 2 percent, the efficiency increases, but the oxygen transfer capacity drops quickly. At a gas-to-water flow ratio higher than 4 percent, the oxygen transfer capacity increases, but the efficiency starts to decrease rapidly.

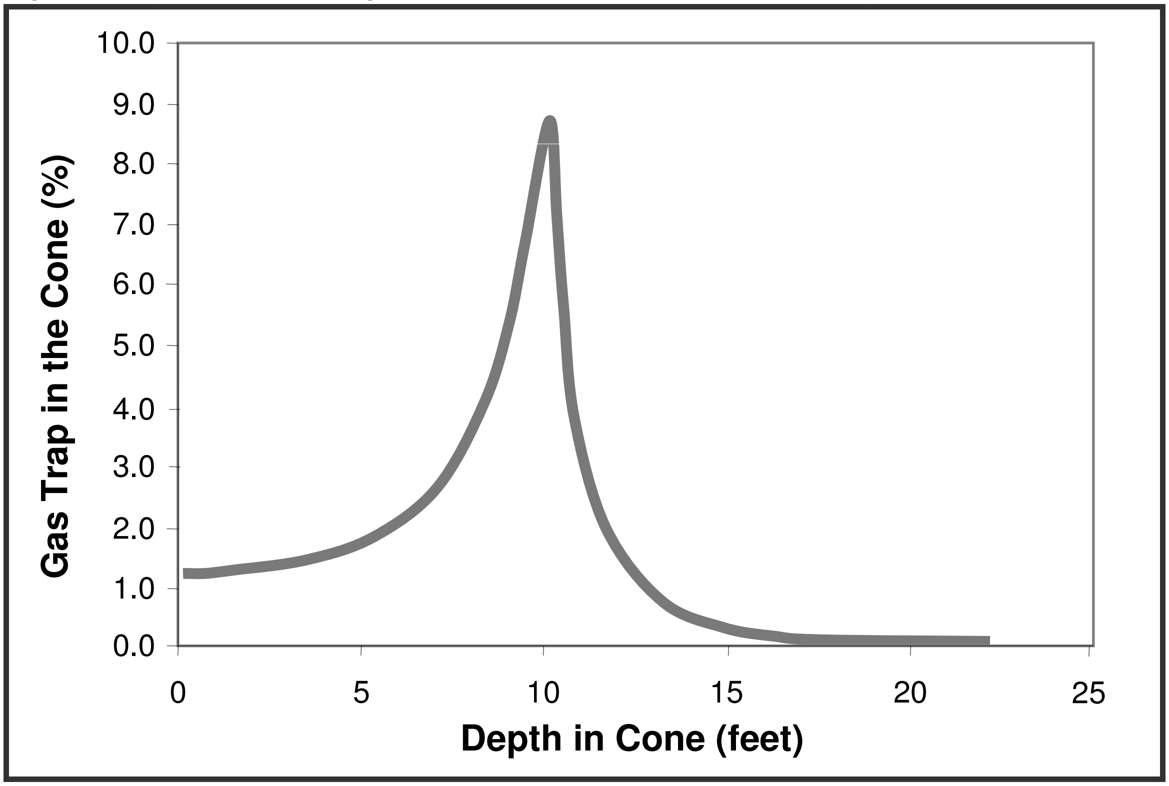
Energy Losses

Field data from the Speece Cone installed at Martin Logan Dam, Alabama showed consistent headloss through the cone for approximately 6 feet for the 15-foot-high cone under the various water flow conditions. Based on this observation, a 30 percent of cone height headloss through the cone was assumed.

Gas Trap

One special phenomenon associated with the Speece Cone is the gas trap or hold-up in the cone as a result of equilibrium of downward water velocity and bubble rise velocity. Figure 25 shows the gas hold-up as a percentage of gas per unit volume of gas and water mixture. The water velocity decreases with depth due to the slope of the cone and, the bubble size and velocity

**Figure 25. Speece Cone Design Evaluation: Gas Hold-Up vs. Cone Depth**




decreases as the bubble travels down the cone with increasing hydraulic pressure and oxygen transfer. At certain depths and operational conditions, the bubble velocity relative to the cone is zero where gas hold-up occurs. The depth at which the highest gas trap occurs depends on the initial water velocity and the initial gas bubble size. If gas is introduced into the cone faster than the gas transfer from gas-to-liquid phase, gas can accumulate inside the cone and the gas trap could cause a hydraulic barrier or "air-lock". A gas release tube is therefore needed to release the pressure.

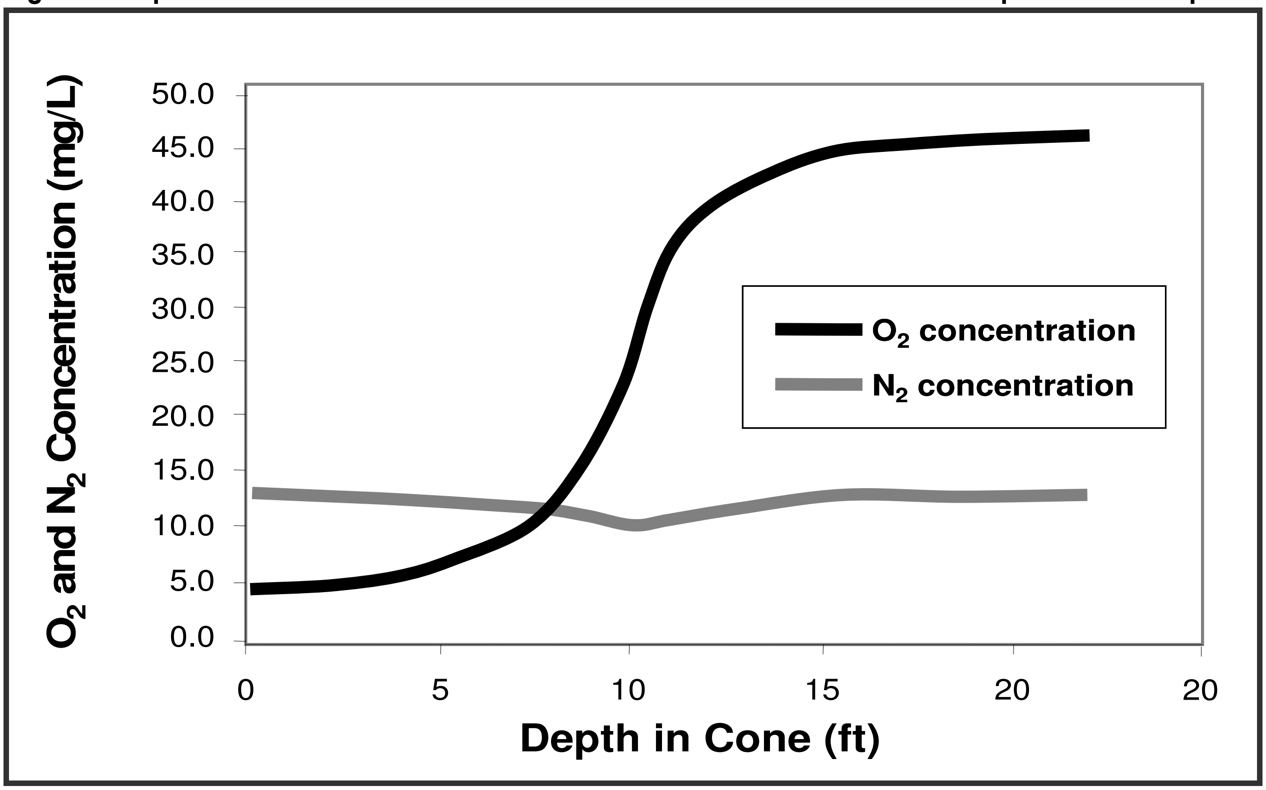
### *Formulation of Alternative Configurations*

A number of Speece Cone design alternatives were evaluated using the model simulations. Alternatives were evaluated by varying hydrostatic pressure in the cone, water flow rates, gas flow rates, cone height and dimensions. The following paragraphs summarize how three Speece Cone configurations where selected for demonstration purposes and how a single configuration best meets the objectives of this study. Alternative configurations for the Speece Cone were developed by evaluating the internal dissolved oxygen concentrations, oxygen transfer efficiencies, and gas and liquid flow rates.

Internal Dissolved Oxygen Concentrations

Figure 26 shows the DO concentration along the depth of the Speece Cone from top to bottom. The rate of change or slope of the DO concentration changes over depth as a result of changes in saturation DO, area of boundary layer of liquid and gas, gas trap percentage ($\varepsilon_g$) and bubble velocity relative to the cone. The highest transfer occurs at the cone depth where the highest gas trap occurs.  Also shown in Figure 26 is the dissolved nitrogen gas concentration. Nitrogen stripping occurs at the beginning of the process. As the nitrogen gas saturation concentration increases with the increasing hydraulic pressure, the stripped nitrogen gas starts to re-dissolve into water.

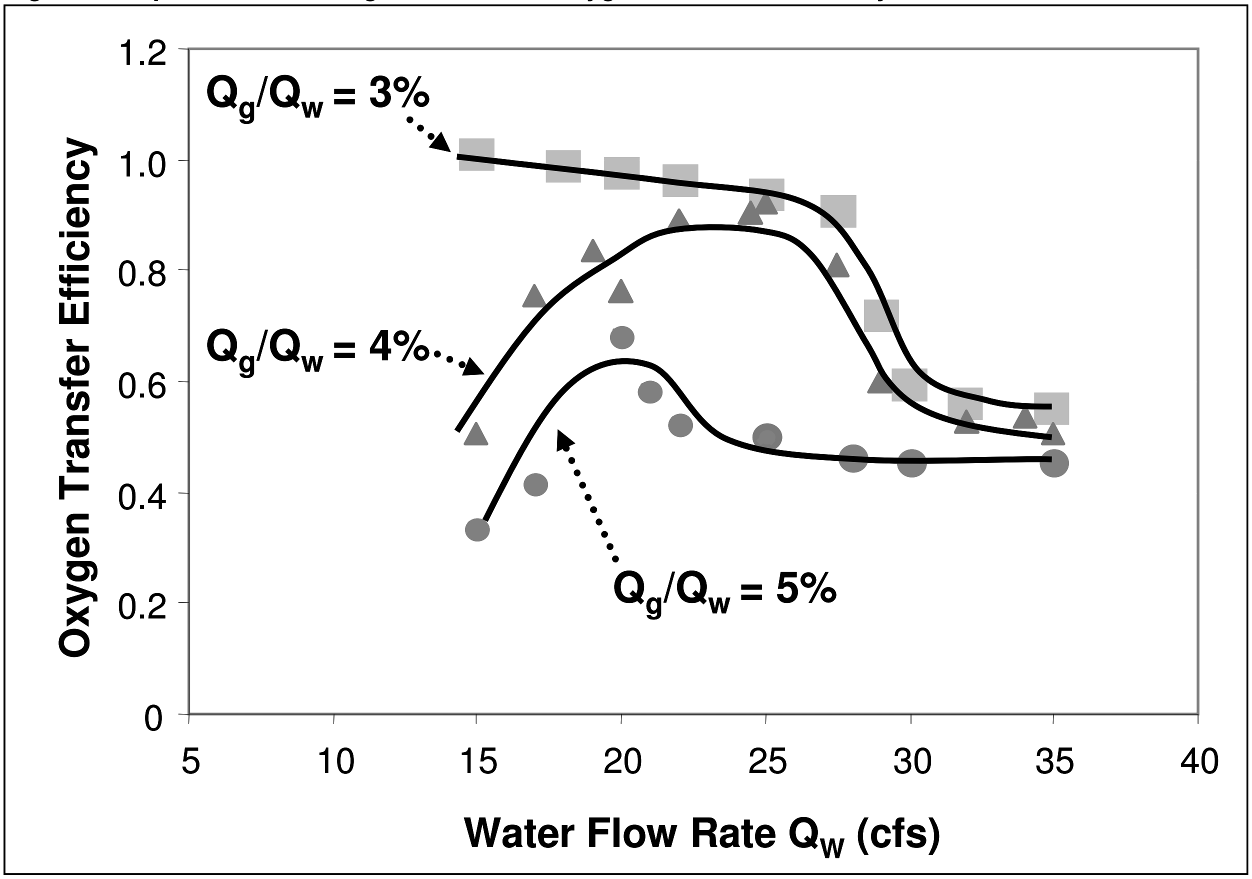
**Figure 26. Speece Cone Model Results: DO and $N_2$ Concentrations at Different Speece Cone Depths**




Oxygen Transfer Efficiency

Figure 27 shows the oxygen transfer efficiency at different water flow rates and oxygen feed as a percentage of water flow. The top and bottom radius and height of the cone body and skirt evaluated were 0.82, 4.59, 4.99, and 15.09 feet, respectively. The available water depth at the DWSC is 30 to 35 feet. The water depth above cone top is therefore about 10 feet. At the lower percentage of gas feed ratio (3 percent), the oxygen transfer efficiency is 95 to 100 percent when the water flow rate is less than 27 cfs, indicating sufficient contact time to transfer nearly all the

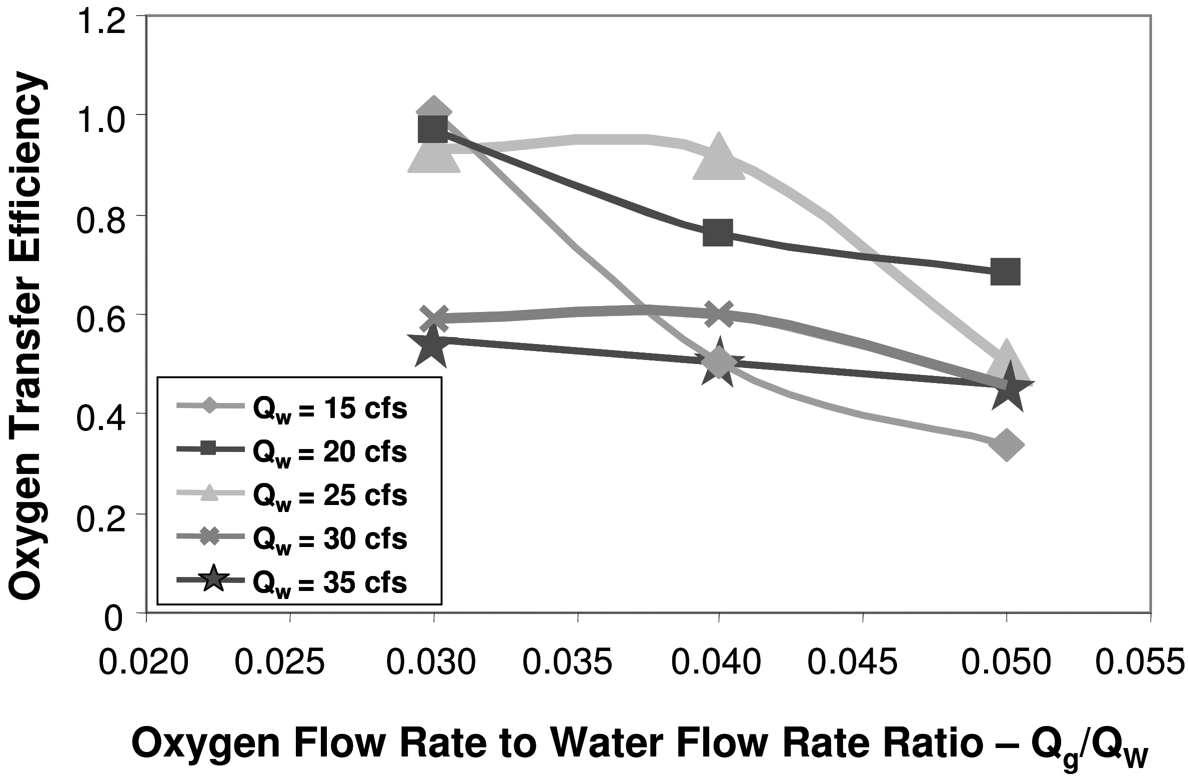
**Figure 27. Speece Cone Design Evaluation: Oxygen Transfer Efficiency vs. Water Flow Rates**




oxygen supplied to the system. At a water flow rate above 27 cfs, the retention time is not long enough to allow complete transfer of oxygen. At higher oxygen feed ratios (4 and 5 percent), the efficiency increases initially as the water flow rate increases. This is because at a similar water flow rate, a higher gas feed rate causes initial bubble size to increase. This results in a higher gas trap percentage in the middle of the cone and less gas and liquid contact area available for oxygen transfer. The oxygen transfer drops dramatically beyond the gas hold-up points. Then, as the water flow rates increase beyond a certain point, the efficiency begins to drop again due to shorter contact time.

Figure 28 shows the oxygen transfer efficiency as a function of the water flow rate and with different oxygen feed ratios. For the flow range studied, at any given water flow rate, the oxygen transfer efficiency decreases as the oxygen feed ratio increases. At a given gas-to-water flow ratio, the efficiency initially increases with the increase of water flow rate. As the flow rate becomes too high, the efficiency starts to decrease. Figure 28 indicates that the optimal operation range is at a water flow rate of 20 to 25 cfs, with an oxygen gas-to-water flow ratio of 3 to 4

**Figure 28. Speece Cone Design Alternative Evaluation: Oxygen Transfer Efficiency vs. Gas to Water Flow Rate Ratios**

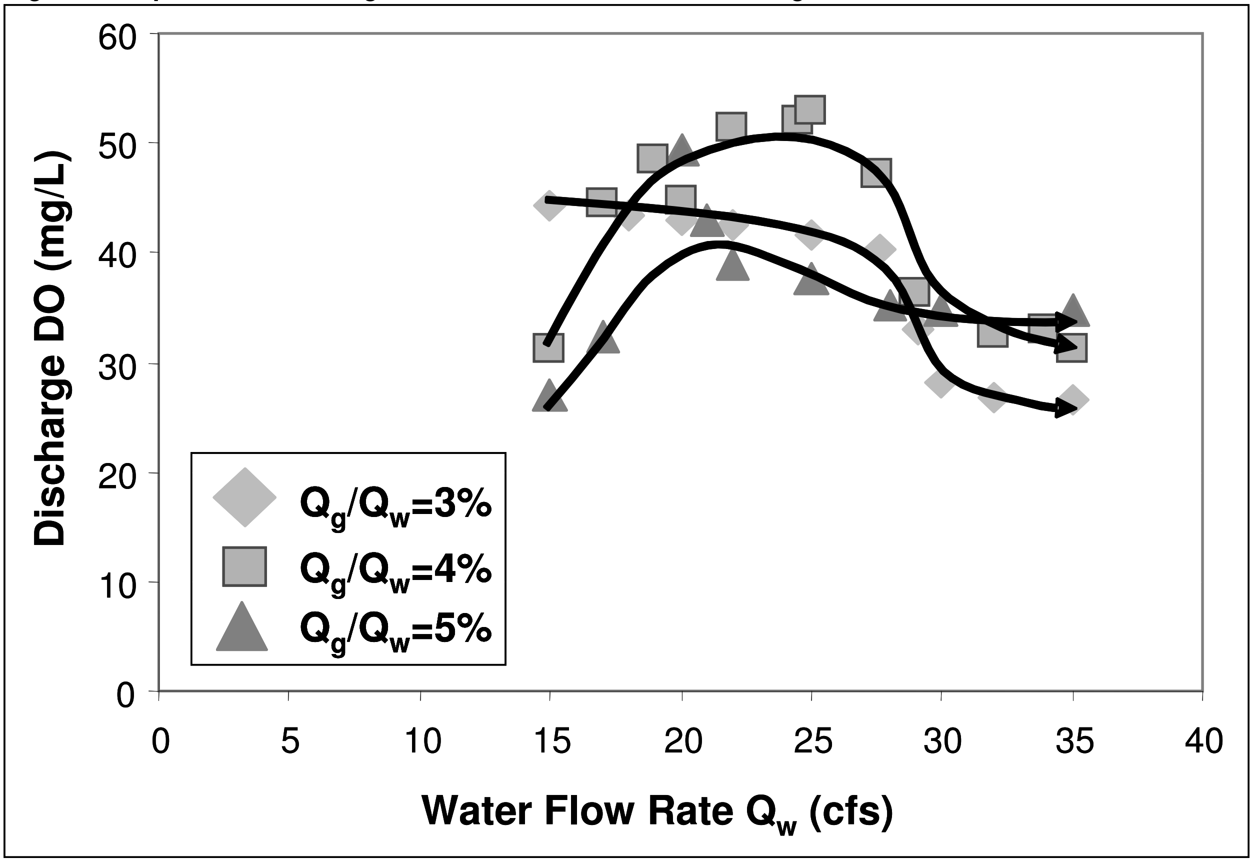



percent. This is consistent with the evaluation results shown in Figure 27. Further, the trends are consistent with field data obtained from Speece Cone at Martin Logan Dam.

Discharge DO Concentrations

Figure 29 shows the discharge DO with different water flow rates and oxygen feed ratios. The discharge DO shows a similar pattern consistent with the oxygen transfer efficiency as shown in Figure 28. At a low gas feed ratio (3 percent), a relatively consistent discharge DO of about 40 to 45 mg/L can be achieved. At the same gas feed ratio, the discharge DO decreases as the water flow rate increases above 30 cfs. With higher gas feed ratios (4 and 5 percent), the discharge DO decreases when the water flow rate is too low or too high. This is due to the gas hold-up that occurs with low water flow rates and less contact time at high water rates as described above. The optimal operational condition for discharge DO would be at a water flow rate from 20 to 25 cfs and with a gas feed ratio of 4 percent. At this condition, a discharge DO of 45 to 50 mg/L can be achieved.

**Figure 29. Speece Cone Design Alternative Evaluation: Discharge DO vs. Water Flow Rate**




<u>Oxygen Transfer Capacity</u>

Oxygen transferred as a function of water flow rates at different gas feed ratios is shown in Figure 30. At the optimal operational range specified via previous evaluation, about 5,000 to 6,000 lbs/d of oxygen can be transferred at a water flow rate of 20 to 25 cfs with a gas feed ratio of 4 percent. Two Speece Cones will be required to meet the oxygen transfer goal of 10,000 lbs/d of oxygen.

## Summary of Evaluation Results

After investigating the most sensitive operation and configuration parameters that affect oxygen transfer performance within the Speece Cone, three alternative configurations were selected for further evaluation in terms of total cost and physical constraints. The three alternatives are summarized in Table 14. Configuration A uses the water depth available in the DWSC. Configuration B uses a pump to increase the pressure in the system. Configuration C uses a larger cone than Configurations A and B, and uses a pump to provide higher pressure in the system.

**Figure 30. Speece Cone Design Alternative Evaluation: Amount of Oxygen Transferred vs. Water Flow Rate**

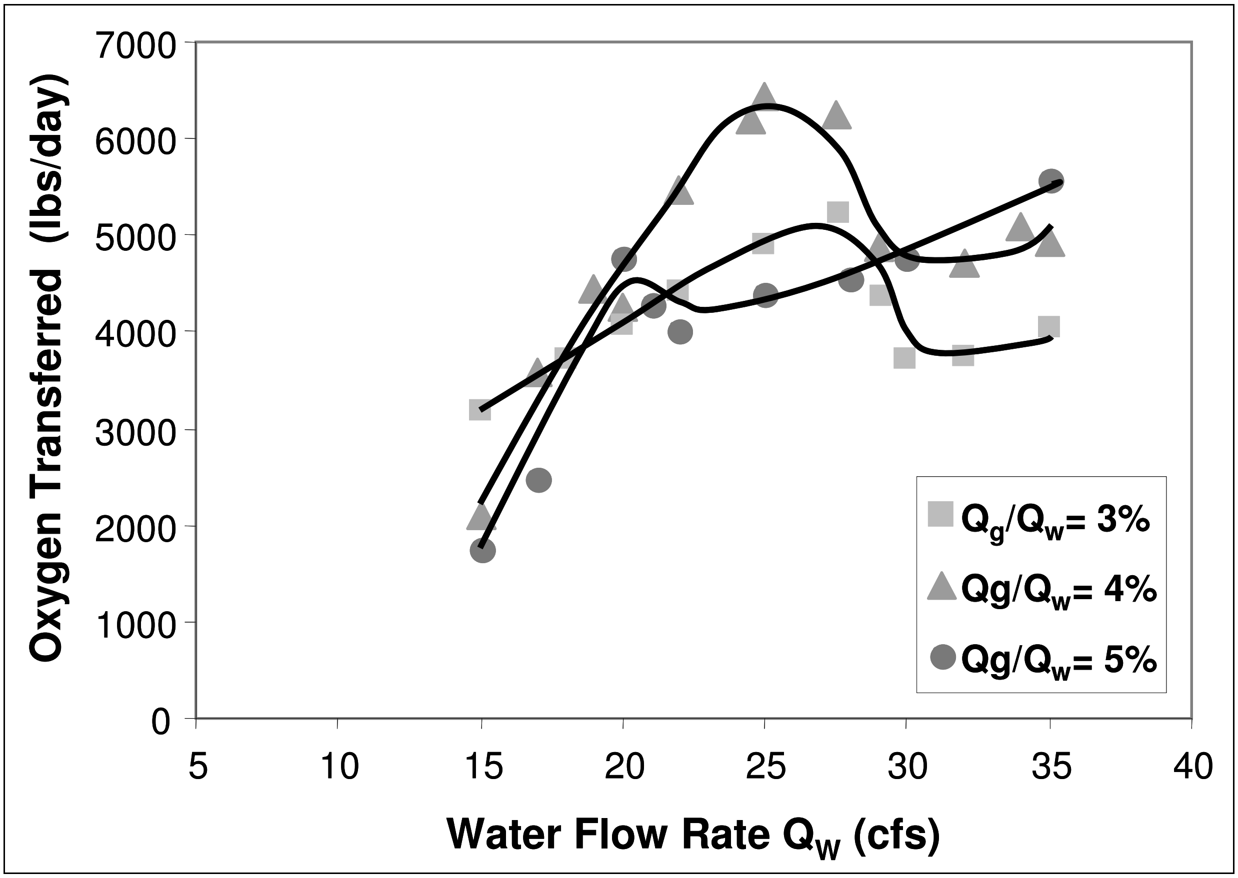



**Table 14. Summary of Design and Operation Conditions for Speece Cone Alternatives**

| | | Symbol | Unit | A | B | C |
|---|---|---|---|---|---|---|
| Design Condition | Water head at the top of cone | D | ft | 10 | 35 | 35 |
| Speece Cone Configuration | Speece Cone top radius | $R_1$ | ft | 0.83 | 0.83 | 1.8 |
| | Speece Cone bottom radius | $R_2$ | ft | 4.5 | 4.5 | 9.4 |
| | Cone height | h | ft | 15 | 15 | 30 |
| | Number of Speece Cones needed | -- | -- | 2 | 2 | 1 |
| | Water flow rate | $Q_w$ | cfs | 24 | 25 | 105 |
| | Gas-to-water flow rate ratio | $Q_g/Q_w$ | % | 4 | 3 | 2 |
| | Correction factor | α | -- | 0.8 | 0.8 | 0.8 |
| | Correction factor | β | -- | 0.95 | 0.95 | 0.95 |
| | Retention time in the cone | t | s | 29-31 | 28-31 | 16 |
| Oxygen Transfer | Initial DO concentration | $C_0$ | mg/L | 5.2 | 5.2 | 5.2 |
| | Discharge DO concentration | $C_e$ | mg/L | 50 | 44 | 21 |

| | | Symbol | Unit | A | B | C |
|---|---|---|---|---|---|---|
| Performance | Initial gas bubble size | $R_o$ | ft | .005 | .006 | .013 |
| | Oxygen transferred per cone | $O_2$-trans | lbs/d | 5,000 | 10,000 | 10,000 |
| | Average oxygen transfer efficiency | e | % | 85 | 95 | 72 |
| | Oxygen supply required per cone | -- | lbs/d | 5,900 | 5,300 | 13,900 |
| | Total oxygen transferred | -- | lbs/d | 10,000 | 10,000 | 10,000 |
| | Total oxygen supply required | -- | lbs/d | 11,800 | 10,550 | 13,900 |
| Annual Oxygen Costs (in thousands) | | $ | $US | 93.3 | 75.2 | 101.1 |
| Power Requirements | | | hp | 60 | 240 | 690 |
| | | | kW | 80.5 | 322 | 925 |
| Construction Costs (in millions) | | $ | $US | 1.88 | 2.04 | 2.85 |
| Annual O&M Costs (in thousands) | | $ | $US | 152 | 160 | 253 |
| Field Data Available | | -- | -- | Yes | Yes | No |

The rationale and discussion of results associated each of the alternative configurations are provided in the following paragraphs.

### *Alternative Configuration A*

Configuration A uses a Speece Cone with a top radius of 0.83 feet and a bottom radius of 4.5 feet. The height of the Speece Cone is 15 feet. The physical configuration of this Speece Cone is similar to configurations already in operation elsewhere. This configuration has an operating pressure of 15 feet of hydraulic head, much less than the other Speece Cones in operations. This limiting operating pressure is due to the limited depth available in the DWSC. Observed Speece Cone performance is enhanced by higher operating pressures typically associated with installations at a depth of 100 feet for more. Thus, two Speece Cones are needed to produce the design goal of 10,000 lbs/d.

### *Alternative Configuration B*

In order to enhance oxygen transfer efficiencies, the same two Speece Cones shown in Configuration A are subjected to higher operating pressure in Configuration B. Because of the lack of hydrostatic forces available, operating pressures within the cone were increased by mechanical means. In this configuration, two 125 hp pumps are needed to create 35 feet of hydraulic head at the top of the Speece Cone. The result is higher oxygen transfer efficiency at higher capital and O&M costs.

### *Alternative Configuration C*

The objective of Configuration C was to evaluate the possibility of transferring 10,000 lbs/d with the use of a single Speece Cone. The size of the Speece Cone was doubled so that the top cone radius was 1.8 feet while the bottom radius was 9.4 feet. The results show that by doubling the size of the Speece Cone, the operational requirements such as pump horsepower and flow rate are at least tripled. In order to transfer 10,000 lbs/d of oxygen with a single cone, 690 horsepower is required to force 105 cfs of water through the cone with an initial hydraulic head of 35 feet. The associated O&M costs double, as well.

## Performance Conclusions

Evaluation and selection of the preferred Speece Cone configuration was conducted using the factors presented in Table 14. Conclusions associated with the evaluation process suggest the following about the Speece Cone.

1. A linear increase in the size configuration and operational parameters of the Speece Cone system does not directly correlate with an increase in oxygen transfer efficiency. In order to maintain transfer efficiencies with larger cones, liquid and gas flow rates and internal cone pressures must be increased by a factor of four. The Speece Cone size was doubled for Configuration C. As a result, pumping requirements increased from 25 to 105 cfs and the corresponding horsepower increased from 240 to 690 hp. The result, even with the increase in pumping regime, was a decrease in transfer efficiency of 23 percent, from 95 percent to 72 percent. This has significant implications to operation costs and oxygen supply costs.
2. Though all the alternatives provide sufficient oxygen transfer capacity to meet the minimum design requirement of 10,000 lbs/d, total horsepower requirements differ based on the cone size and the associated pressures needed. Higher pump power is needed for Speece Cone Configuration B. Although Configuration B produces higher oxygen transfer efficiency and requires less oxygen, annual O&M costs are sacrificed due to the increased power requirements needed for operation.

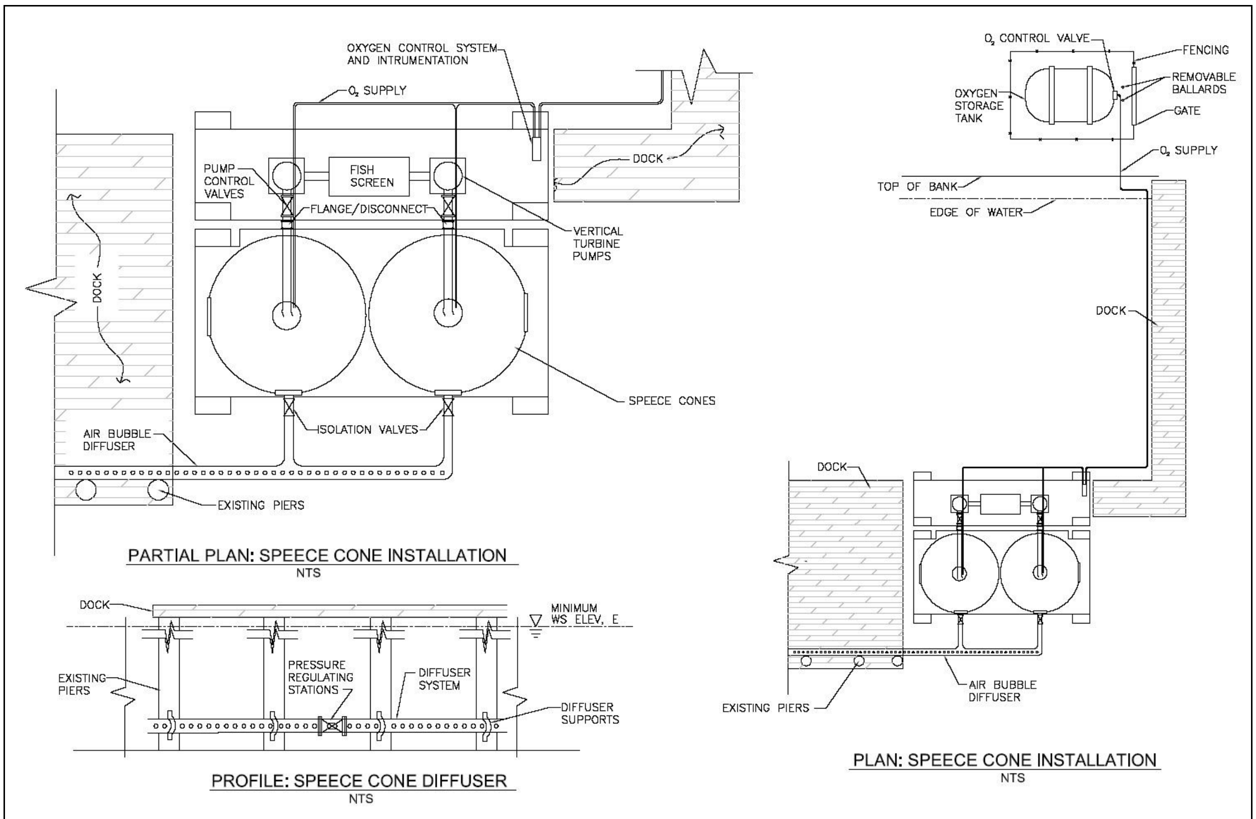
## Recommended Speece Cone Configuration

The preferred Speece Cone design was selected based on the factors presented in Table 14. All alternatives provide sufficient oxygen transfer capacity to meet the minimum design requirement of 10,000 lbs/d. Total horsepower requirements differ due to the different design pressures within the cone. Greater pump power is needed for Configuration C than Configuration B, and greater pump power is needed for Configuration B than A. Although Configuration B produces higher oxygen transfer efficiency and requires less oxygen than both Configuration A and C, annual O&M costs are sacrificed due to the increased power requirement needed for operation. Thus, it is reasonable to select the most energy efficient design requiring less annual O&M funds. Configuration A was selected as the preferred Speece Cone design alternative.

### *Implementation*

Implementation of the Speece Cone Configuration A would include the construction of both onshore and offshore facilities. Onshore facilities would include an oxygen supply system and a 9,000-gallon storage tank. Offshore facilities would include a relatively short dock or floating walkway, an equipment platform with automated equipment hoist, pumping equipment, the Speece Cone assemblies, and a diffuser system. A pumping platform would provide a location where two 30 hp vertical turbine pumps can supply raw water extracted from the DWSC at a minimum flow rate of 24 cfs. The pumped water would be supplied to each Speece cone via a 12-inch discharge header. The water would be supplied with a hydraulic pressure head of 10 feet. At the cone skirt, a 12-inch pipe would transport the oxygenated water to the diffuser system to be discharged into the receiving water. Pressure regulating stations can be placed along the diffuser lateral to equalize the discharge of oxygenated water, or to transport oxygenated water to one section of the diffuser. A plan of potential Speece Cone installation is diagramed in Figure 31.

**Figure 31. Speece Cone Installation Plan**



## *Design Elements*

The specific design elements associated with the recommended Speece Cone configuration are described in Table 15.

**Table 15. Summary of Speece Cone Design Elements**

| Design Element | Description |
|---|---|
| *Site Work* | |
| Foundations and Slabs | Concrete foundations are required for the 9,000 gallon oxygen supply tank. The slab for the 9,000-gallon oxygen storage tank must be at least 20 feet long by 12 feet wide. An additional 12 x 12-foot slab is required near the oxygen control and refilling equipment. |
| Pavement | Six inches of aggregate base below 3 inches of asphaltic concrete shall provide a clean, orderly, and drivable working area surrounding the oxygen storage facility. A pavement area 30 feet long by 30 feet wide is required. |
| Fencing | Chain link fencing can be used to enclose and secure the oxygen supply equipment. At least 120 feet of 8-foot-high fencing is required. One 12-foot gate can be installed to allow for entry of personnel and vehicles. |
| *Structures* | |
| Docks | A dock or floating walkway will be constructed to the equipment platform located approximately 30 to 50 feet from the edge of bank. |
| Equipment Platforms | The equipment platform should include a stationary platform where the pumping and oxygen regulating equipment can be installed, operated, and maintained. A larger section of automated platform should be constructed with the ability to lower or raise the two Speece Cone assemblies in and out of the DWSC. |
| *General Equipment* | |
| Vertical Turbine Pump, motor, casing, and impeller | Two 30 hp pump motors shall power two vertical turbine pump assemblies. Appropriate casing depth, impeller size, and number of stages should be determined during final design. |
| Fish Screen | One barrel-type fish screen capable of meeting NOAA Fisheries requirements with a operation criteria of 25 cfs can supply water to both pumps. |
| *Mechanical* | |
| Piping | Ductile iron piping with a suitable coating can be used for pump supply and discharge headers. Under the stated design conditions, one 12-inch pipe is expected to supply water from each pump to each Speece Cone. A single 20-inch discharge header can be used to transport oxygenated water from the Speece Cones to the diffuser system. |
| Pump Control Valves | Twelve-inch pump control valves shall be used to ramp or throttle flows as needed to prevent surge within the piping system. |
| Isolation Valves | Up to three butterfly valves may be placed at key locations to isolate pumping equipment during operation or for maintenance purposes. |
| Throttling Valves | Two throttling valves will be placed at the cone discharge. These valves can be used to increase or decrease flows or backpressure within the Speece Cone. |
| Pressure Regulating Stations | Pressure regulating stations/valves can be used to equalize pressure within the diffuser system that discharges oxygenated water to the receiving water. These valve stations can be used to ensure equal discharge across the entire diffuser system or to direct oxygenated water to specific areas within the 800 foot reach of diffuser piping. Regulating stations are controlled by the electronic control equipment and programming located with the pump facility housing. They can be controlled via radio transmission or by wire feed. |
| *Oxygen Supply* | |

| Design Element | Description |
|---|---|
| Oxygen Storage Tank | A 9,000-gallon storage tank shall be provided and installed by a commercial oxygen supplier. Oxygen storage equipment is available on a monthly rental basis. |
| Oxygen Control and Supply Equipment | Electronic instrumentation and an oxygen gas control valve shall be used to measure and control oxygen supply rates to the system. |
| *Special Construction* | |
| Speece Cone assembly | Two Speece Cones and the associated appurtenances will need to be prefabricated at .a facility that specializes in steel piping fabrication. |
| Diffuser Lateral | A single 24-inch liquid diffuser lateral approximately 800 feet long and constructed of high density polyethylene pipe shall be used to transport and disburse oxygenated water to the receiving water. Orifice sizes shall be designed such that the head loss through the orifices is 10 times that of the head loss through the pipe. Orifice spacing and size shall be considered during final design. Underwater construction and installation activities are required. |

### *Design Considerations*

The following paragraphs discuss additional key design considerations to be evaluated during field testing and final design of the Speece Cone system.

Effective Bubble Size and Gas-to-Liquid Flow Ratio

As discussed earlier in the U-Tube evaluation, the effective bubble size was calculated for each operational condition. It is assumed that for each different operational condition (i.e. a specific gas flow rate, water flow rate, and Speece Cone size) the effective bubble size would change due to the varying hydraulic conditions within the Speece Cone and especially at the location where oxygen gas is emitted into the cone. This variance in hydraulic forces causes bubbles to coalesce or break apart depending on the internal Speece Cone dynamics. As described previously, this dynamic was examined with the use of a calibrated computer model developed for this study. Although the model estimates represent real world conditions based upon empirical field results, using this assumption within the design process complicates the evaluation of the results.

In order to simplify the design process, it is possible to assume a fixed initial bubble size. This may be achieved by installing fine bubble diffusers that produce a known bubble size into the Speece Cone rather than a gas nozzle with a single orifice. The use of a fine-bubble diffuser would ensure that the initial bubble size would meet a specific size requirement at the discharge point. As the gas and liquid mixture travels through the Speece Cone system, the bubble sizes would decrease due to the increase in hydrostatic pressure and the mass transfer of oxygen to the water. Thus, since system performance improves with smaller bubble sizes, the use of a fixed initial bubble size during performance calculations would provide a conservative estimate while the actual system performance would be better than the calculated estimate.

This assumption would simplify the design process by eliminating a variable from the model and would provide more intuitive conservative results.

#### *Further Recommendations*

Both the down-tube velocity and the initial bubble size affect oxygen transfer and Speece Cone performance greatly. It is recommended that a scaled Speece Cone field test be conducted in order to further our knowledge of these two parameters, how these parameters affect system performance, and how the use of these two parameters can be better understood.

# BUBBLE PLUME AERATION

## Overview of Bubble Plume Technology

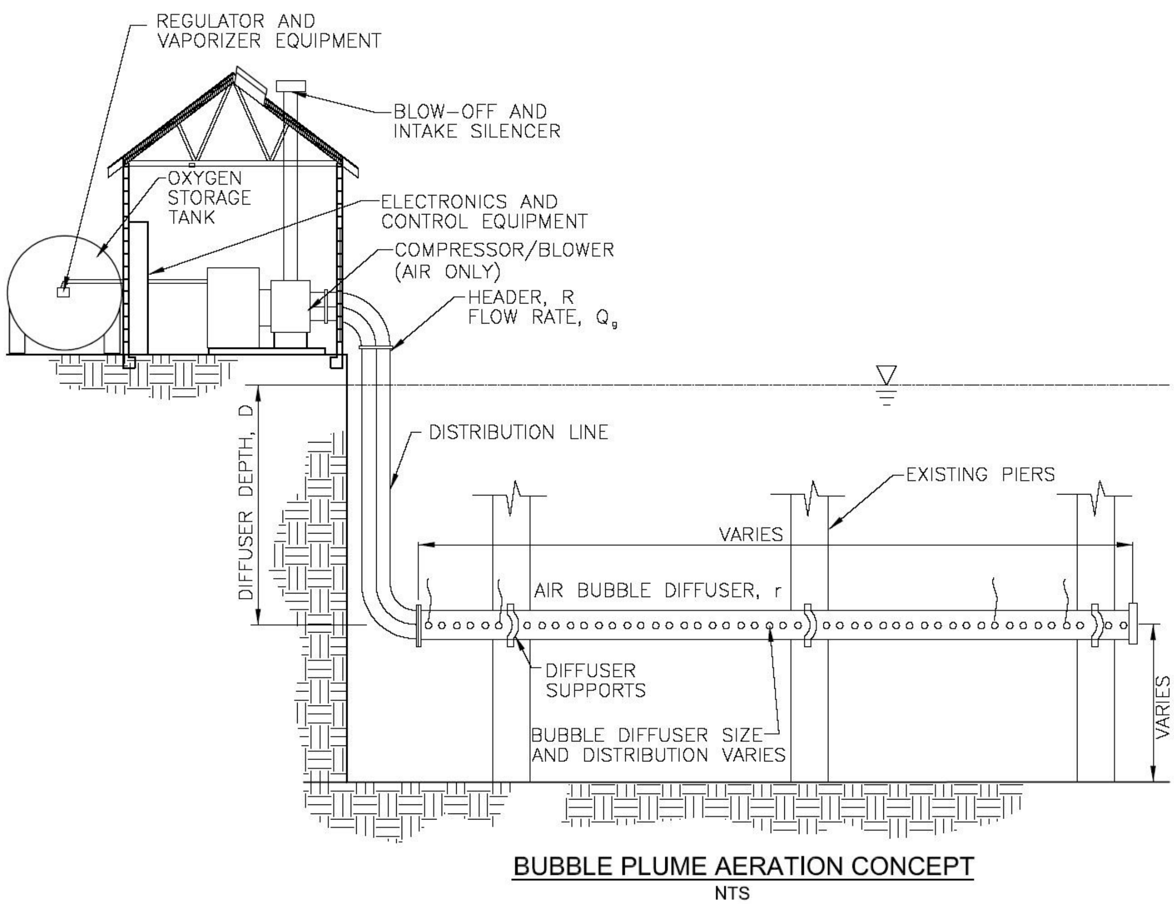
### *Configuration Description*

Bubble diffusers emit air or oxygen gas bubbles into a waterbody allowing them to travel freely from the discharge point to the water's surface. During upward travel, bubbles transfer oxygen to the surrounding waterbody and thereby decrease in size. For a bubble that is pure oxygen, the difference in volume between the initial bubble size and the final bubble size equals the volume of oxygen transferred into the water.

Many types of bubble diffusers exist. Commercially available bubble diffusers include, but are not limited to porous membranes, ceramics, stones, and hose type bubble diffusers. Diffusers may be configured to produce fine (small) or course (large) bubbles. This study considers the use of bubble hose diffusers because of their ease of installation and operation, relatively lower unit costs, and moderate oxygen transfer efficiency.

Generally, a bubble hose diffuser consists of porous hosing laid across the bottom of a waterbody. The diffuser is filled with compressed air or pressurized pure oxygen from an onshore supply facility (see Figure 32). As the gas passes through the diffuser apparatus, it creates an upwelling of oxygen-rich water in the form of bubble plumes. Oxygen from these plumes is transferred into the surrounding water as oxygen gas trapped in the rising bubble plume is released. While the bubbles travel upward, they also carry volumes of water with them creating an upwelling of water. This additional water circulation provides additional mixing and enhances the oxygen transfer efficiency.

**Figure 32. Typical Bubble Plume System**




## *Oxygen Transfer*

Three major factors determine the oxygen transfer rate and efficiency for Bubble Plume aerators, including water depth, specific gas flow rate, and the source of oxygen (compressed air or pressurized oxygen).

Generally, oxygen transfer efficiency increases proportionally to water depth. This increased efficiency is a result of the longer contact time between the gas bubble and the water when Bubble Plume systems are placed in deeper waters.

Oxygen transfer increases proportionally as the gas flow rate increases. Therefore, the total length of diffuser hose required to deliver 10,000 lbs/d of oxygen is shorter at higher gas flow rates. However, the oxygen transfer efficiency decreases as the gas flow rate increases, therefore more oxygen supply is needed to achieve the same oxygen transfer goal.

If compressed air is used as the gas source, it must be introduced into the aeration system via mechanical pumping (increasing overall annual O&M costs). Because it is pressurized, using pure oxygen eliminates the need for mechanical air pumping equipment, thus reducing annual power costs.

### *General Performance*

General performance expectations of a Bubble Plume aeration system are presented in Table 16.

**Table 16. Performance of Bubble Plume Oxygenation Systems**

| Item | Description |
|---|---|
| Material Cost | The unit cost for bubble hose diffusers is generally much less than unit costs for other aeration technologies. Unit costs for bubble hoses generally range from $5.00 to $25.00 per foot. |
| Capital Cost | Capital costs are generally lower than other aeration technologies because of their simplicity. Systems using pure oxygen generally require no pumping equipment due to the use of pressurized tanks. Capital costs associated with air blowers or compressors are generally less than liquid pumps. |
| Oxygen Transfer Rate | Oxygen transfer rates have been recorded within a range of 15% to 40% using ambient air as an oxygen source. Oxygen transfer rates range from 30% to 90% for pure oxygen systems. |
| Energy Cost | Operation costs associated with air blowers or compressors are generally less than liquid pumps due to the need for less horsepower. |

## Evaluation of Modified Bubble Plume Configurations

### *Oxygen Transfer Model Development*

A model for Bubble Plume aeration oxygen transfer performance and efficiency evaluation was developed using basic aeration mass transfer equations and empirical models developed for a rubber soaker hose by DeMoyer et al (2001). Two oxygen supply sources were assessed, namely using air versus using pure oxygen. The variables used in the model and basic equations applied to calculate oxygen transfer rate and efficiency are described in the paragraphs below.

### *Variables Used In the Model and Design Conditions*

The configuration parameters and operational conditions used to evaluate oxygen transfer performance of Bubble Plume aeration for this Engineering Feasibility Study are listed in Table 17. The variables used in the model and their definition and units used are listed in Table 18. The gas flow rate range selected is from a survey of hose diffuser manufactures. The gas flow rate for using pure oxygen as an oxygen source is usually lower than using air.

**Table 17. Design and Operation Conditions for Bubble Plume Aeration Model**

| Description | Symbol | Unit | Design Range |
|---|---|---|---|
| **Device Configuration** | | | |
| Diffuser hole diameter | D | ft | .006 to .001 |
| **Operational Conditions** | | | |
| Water depth at diffuser discharge | D | ft | 25 |
| Gas(air) flow rate/ft-hose | $Q_g$ | scfm/ft | 0.2 to 0.5 |
| Gas (oxygen) flow rate | $Q_g$ | scfm/ft | 0.05 to 0.2 |
| Oxygen transfer efficiency (depends on depth)-air | e | % | 20 to 30 |
| Oxygen transfer efficiency (depends on depth)-oxygen | e | % | 50 to 90 |
| Correction coefficient for saturation DO | α | ratio | 0.95 |
| Correction coefficient for transfer coefficient | β | ratio | 0.8 |

**Table 18. Variables and Parameters Used in the Bubble Plume Aeration Model**

| Variable | Description | Unit |
|---|---|---|
| R | Radius of U-Tube at any given depth | ft |
| h | Water depth at the diffuser | ft |
| $Q_g$ | Gas flow rate | scfm |
| E | Elevation at water surface | ft |
| $C_s$-20 | Saturation DO concentration at 20° C and 1 atmospheric pressure | mg/L |
| $C_s$ | Saturation DO concentration at a given temperature (°F) and elevation | mg/L |
| $C_s$ | Average saturated DO at the middle diffuser depth | mg/L |
| $C_i$ | Dissolved DO before aeration | mg/L |
| $P_i$ | Partial gas pressure of oxygen | psi |
| P | Atmospheric pressure at water surface | psi |
| $P_{mid}$ | Hydrostatic pressure at middle of diffuser depth | psi |
| $Ko_L$ | Mass transfer coefficient for oxygen | ft/s |
| H | Henry's constant for oxygen | mole/$m^3$-Pa |
| α | Correction factor for the effect of impurities in water on mass transfer coefficient | ratio |
| β | Correction factor for the effect of impurities in water on the saturated DO concentration | ratio |
| SOTR | Standard oxygen transfer rate at 1 atmospheric pressure, 68 °F and initial DO of zero | lbs/d |
| AOTR | Actual oxygen transfer rate under operational conditions | lbs/d |
| SOTE | Standard oxygen transfer efficiency | % |
| AOTE | Actual oxygen transfer efficiency at operation conditions | % |
| SAE | Standard aeration efficiency | lbs/kW/h |

### *Equations Used In the Model*

The correlations and mass balance equations used for the model development are presented below. The following equations describe the correlation of oxygen transfer rate and efficiency with different gas flow rates and at different water depths. The standard oxygen transfer efficiency (SOTE) is usually determined by the standard oxygen transfer test using air as the oxygen source. The actual oxygen transfer rate (AOTR) under real operational conditions is calculated with corrections for oxygen driving force, temperature, and impurities in the water. When using pure oxygen as the oxygen source, the saturation DO ($C_s$) at oxygen partial pressure of 100 percent of total gas pressure is used instead of 22 percent of total gas pressure. The minimal stripping of $N_2$ gas from liquid to gas is neglected. Equations (8) through (10) are empirical models developed based on field-tested data for a rubber soaker hose by DeMoyer et al (2001). Since these models are specific for this type of hose with an average gas bubble size of 0.006 ft, some deviation may be expected for other types of hoses if the gas bubble size is significantly different. Pilot testing is required to determine the exact oxygen transfer rate and efficiency for other types of hose diffusers, or information can be acquired from manufacturers.

$$C_s = H \times P_i \tag{1}$$

$$\overline{C_s} = C_s \times \frac{P + P_{mid}}{P} \tag{2}$$

$$P = P_s * \exp\left(\frac{-gME}{RT}\right) \tag{3}$$

$$SOTR = K_L \times A \times C_s \tag{4}$$

$$AOTR = SOTR \times \left(\frac{\beta \times \overline{C_s} - C_L}{C_{s20}}\right) \times (1.024)^{T-20} \times \alpha \tag{5}$$

$$SOTE = \frac{SOTR}{OxygenFed} \tag{6}$$

$$SAE = \frac{SOTR}{PowerInput} \tag{7}$$

$$SOTR = 0.0583 \times Qg^{21/27} \times h^{17/29} \tag{8}$$

$$SOTE = 0.21 \times Q_g^{-2/9} \times h^{7/12} \tag{9}$$

$$SAE = 11.47 \times Q_g^{15/22} \tag{10}$$

$$H_N = 1.042 \times 10^{-5} - 2.450 \times 10^{-7} \times T + 3.171 \times 10^{-9} \times T^2 \tag{11}$$

### *Model Calibration and Validation*

The model developed for this Engineering Feasibility Study was calibrated with field data by DeMoyer et al (2001). The oxygen transfer performance was conducted with a 3.51-foot-long permeable rubber bubbler hose at various water depths and standard oxygen transfer rate (SOTR), SOTE and standard aeration efficiency (SAE) were recorded for different conditions. The permeable nature of the bubbler hose allows the formation of fine bubbles with diameters of 0.006 to 0.010 feet. Clean water gas transfer tests were conducted in accordance with American Society of Civil Engineers standard procedures. Two DO probes were used to measure the DO. The system configuration parameters are shown in Table 19.

**Table 19. Configuration Parameters of Bubble Plume Aeration Field Test**

| | Symbol | Value | Unit |
|---|---|---|---|
| Temperature | T | 62.2 to 80.6 | °F |
| Operation depth-inlet | h | 10.8 to 31.6 | ft |
| Bubbler hose length | L | 3.5 | ft |
| Gas flow rate at atmosphere  P/ft tube | $Q_g$ | 0.37 to 1.57 | scfm/ft |
| Oxygen percentage in air | $f_{O2}$ | 21 | % |
| Initial oxygen concentration in water | $C_0$ | 0 | mg/L |

The correlation of the model simulation results to the field data are shown in Figure 33, Figure 34, and

Figure 35. The model simulation results relative to the field data demonstrates that the model is able to adequately simulate the oxygenation performance of Bubble Plume aeration for the specific type of bubbler hose used and at the given operational conditions.

**Figure 33. Bubbler Hose Aeration Model Calibration: Oxygen Transfer Rate vs. Gas Flow Rate**

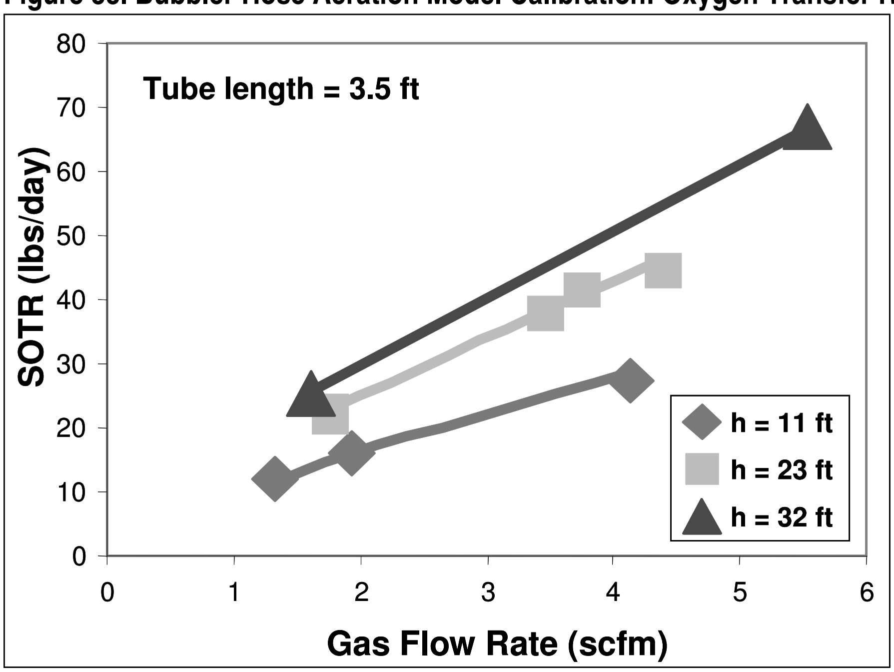


**Figure 34. Bubbler Hose Aeration Model Calibration: Oxygen Transfer Efficiency vs. Air Flow Rate**

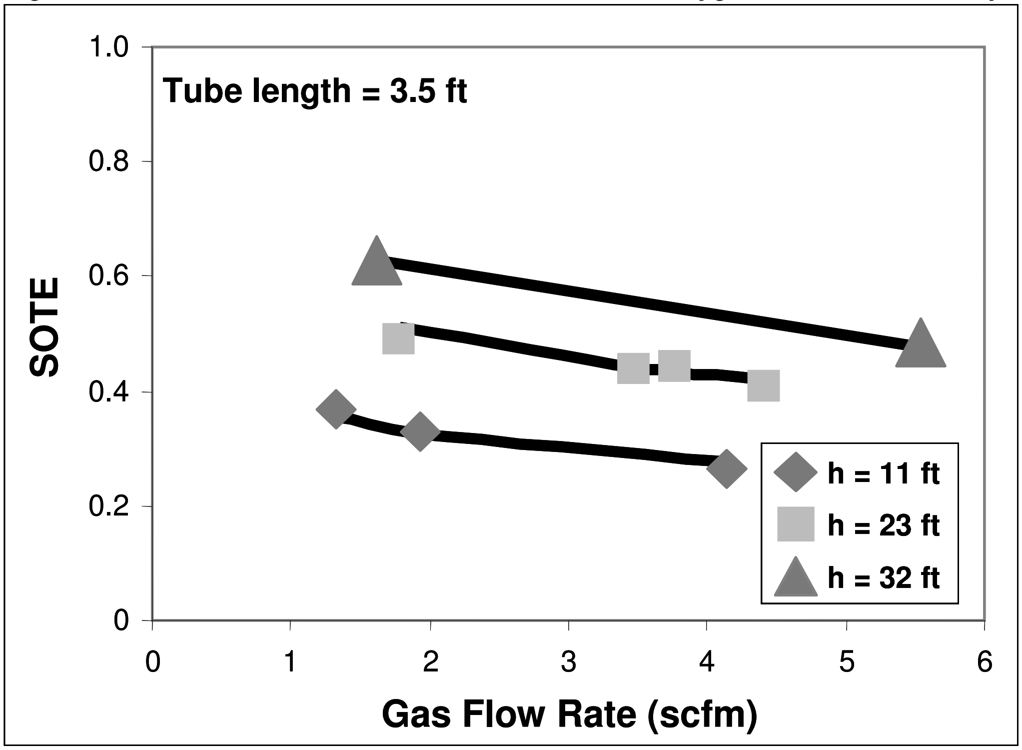
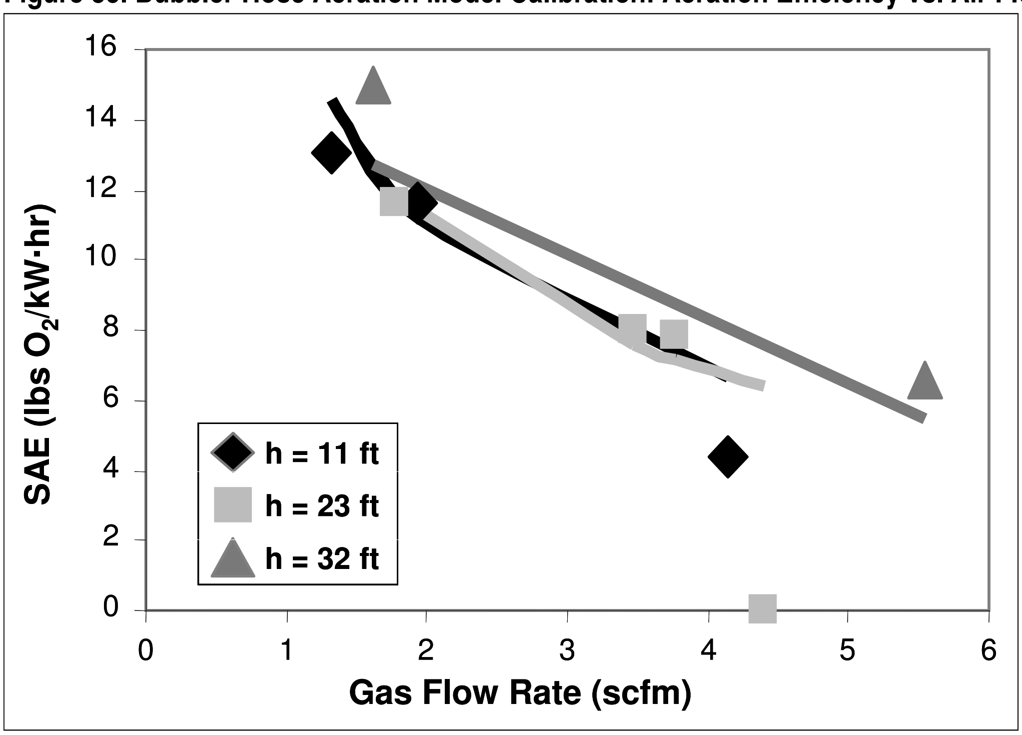



**Figure 35. Bubbler Hose Aeration Model Calibration: Aeration Efficiency vs. Air Flow Rate**



## *Basic Assumptions and Design Criteria*

The configuration parameters and operational conditions that were used to evaluate oxygen transfer performance of Bubble Plume aeration for this Engineering Feasibility Study are listed in Table 20. The gas flow rate range selected for use in the model was obtained from a survey of bubble hose diffuser manufactures. Results from the manufacturer research are summarized in Table 21. The gas flow rate for pure oxygen as an oxygen source is usually lower than air based on the manufacturer's recommendations.

**Table 20. Design and Operational Conditions for Bubble Plume Aeration**

| Description | Symbol | Unit | Design Range |
|---|---|---|---|
| **Device Configuration** | | | |
| Diffuser hole diameter | D | ft | .006 to .010 |
| **Operational Conditions** | | | |
| Water depth at diffuser discharge | D | ft | 20 to 25 |
| Gas( air) flow rate/ft-hose | $Q_g$ | scfm/ft | 0.2 -0.5 |
| Gas (oxygen) flow rate | $Q_g$ | scfm/ft | 0.05 to 0.2 |

**Table 21. Summary of Bubble Hose Manufacturer Recommendations**

| Bubble Hose Type | Specific Gas Flow Rate (scfm/ft) | Unit Cost ($/ft) | Recommended Efficiency | Model Estimated Efficiency |
|---|---|---|---|---|
| **BIOX**[1] | 0.05 | 7 | 100% @ 20 ft depth | 70% at 20 ft |
| **Dryden Diffuser**[2] | 0.15 | 14 | 60% @ 20 ft depth | 55% at 20 ft |
| **Bio-Weave**[3] | 0.2 | 13 | 65% @ 20 ft depth | 52% at 20 ft |
| **TVA - Permeable Rubber Hose**[4] | 1.3 | - | 45% at 20 ft | 43% at 20 ft |

[1]per comm Jim Fynes, June 2004
[2]per comm. Dr. Howard T Dryden, 21 June 2004
[3]per comm Gary Rogers, Aquatic Eco-Systems, Inc. June 2004
[4]DeMoyer et al (2001)

## *Formulation of Alternative Configurations*

Two major alternatives were evaluated using bubbler hose aeration with different oxygen sources, namely air or pure oxygen. For each oxygen source, the oxygen transfer rate, transfer efficiency, and aeration efficiency were evaluated at two different water depths and a range of gas flow rates. The two water depths used were 20 feet and 25 feet, which are based on the river depth at the potential application points in the San Joaquin River. Installation depths of 30 to 35 feet may be possible if a suitable location can be found. The results will improve if installation exceeds a depth of 25 feet.

<u>Use Air as Oxygen Source</u>

The oxygen transfer rates, efficiency and the length of hose needed to meet the design goals were evaluated for operational water depths of 20 feet and 25 feet, respectively. The actual oxygen transfer rate and the hose length required to transfer 10,000 lbs/d of oxygen is a function of the specific air flow rate applied. As shown in Figure 36, at a water depth of 20 feet, the specific AOTR (lbs/d-ft-length hose) ranges from 0.9 to 2.8 lbs/d-ft at a specific air flow rate of 0.2 to 0.5 scfm/ft. The hose length needed is then estimated to range from 3,100 to 7,000 feet.

Figure 37 shows that the oxygen transfer efficiency decreases as the air flow rate increases. At a specific air flow rate of 0.5 scfm/ft, the actual oxygen transfer efficiency is only about 22 to 28 percent.

**Figure 36. Bubbler Hose Aeration Model Results: AOTR and Hose Length Required as a Function of Specific Gas Flow Rate**

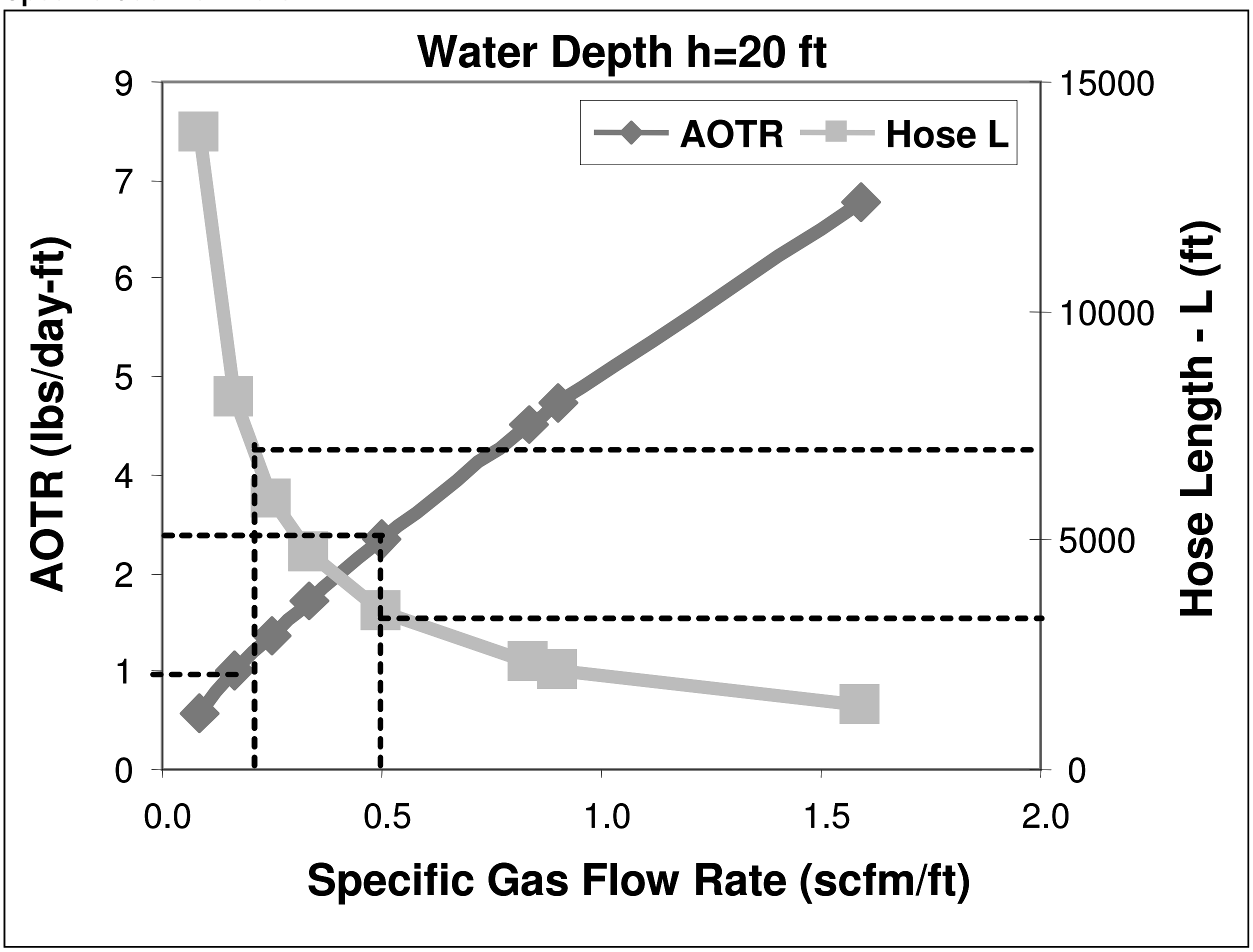


**Figure 37. Bubbler Hose Aeration Design Evaluation: Oxygen Transfer Rate and Efficiency as a Function of Specific Air Flow Rate**

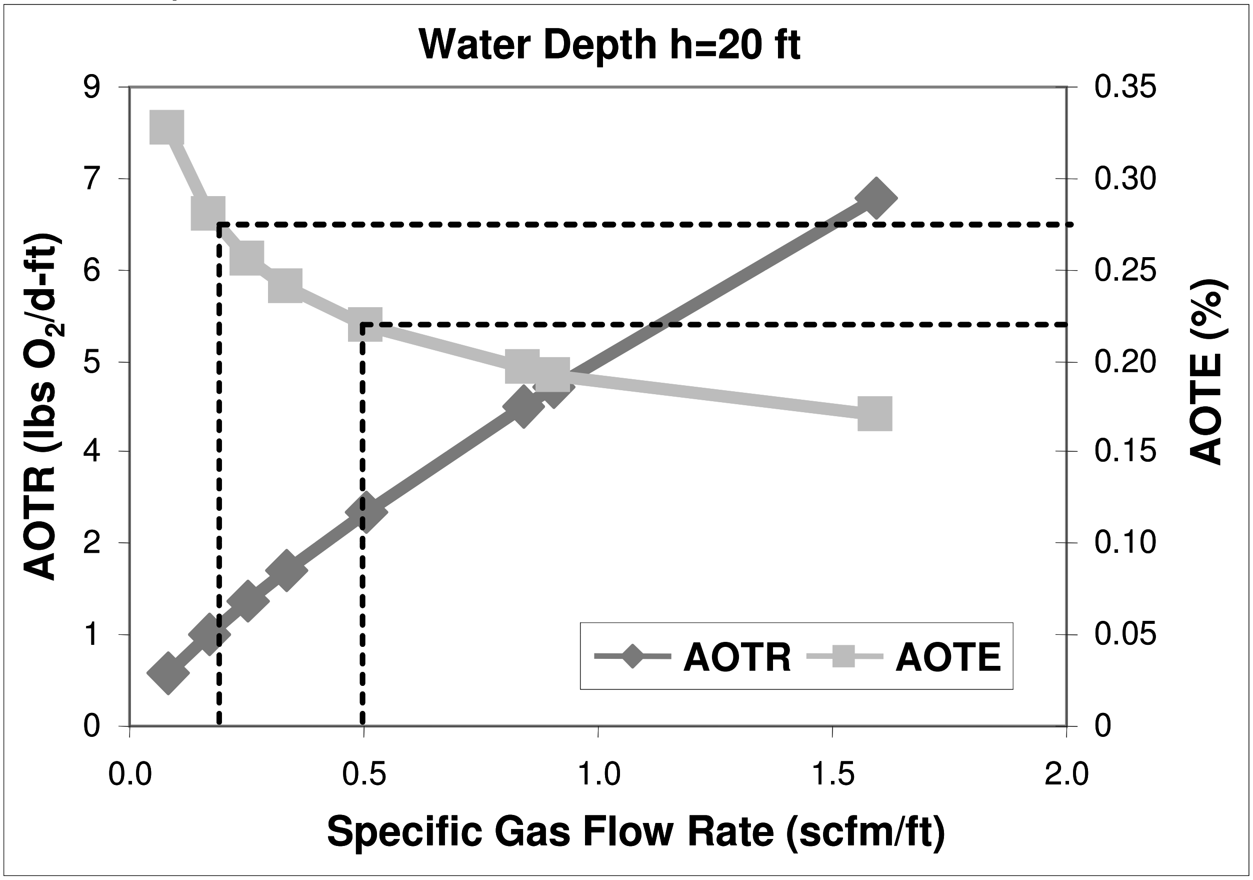



Figure 38 and Figure 39 show a similar oxygen transfer rate and efficiency as a function of specific air flow rates at a water depth of 25 feet. Both the oxygen transfer rate and the efficiency increases as water depth increases. At a specific air flow rate of 0.2 to 0.5 scfm/ft, 3,000 to 5,500 feet of hose will be required to deliver 10,000 lbs/d oxygen at a rate of 1.5 and 3.6 lbs/d-ft hose, respectively. At the same operational condition, the oxygen transfer efficiency is about 28 to 34 percent, which is higher than the efficiency at 20 feet and 22 to 28 percent oxygen transfer efficiency.

In summary, the length of hose required increases as the specific air flow rate decreases, however, the oxygen transfer efficiency and power use efficiency increases as the specific air flow rates decrease. Therefore, a minimization of sum of capital cost and operational cost is desired.

**Figure 38. Bubbler Hose Aeration Model Results: AOTR and Hose Length Required as a Function of Specific Gas Flow Rate**

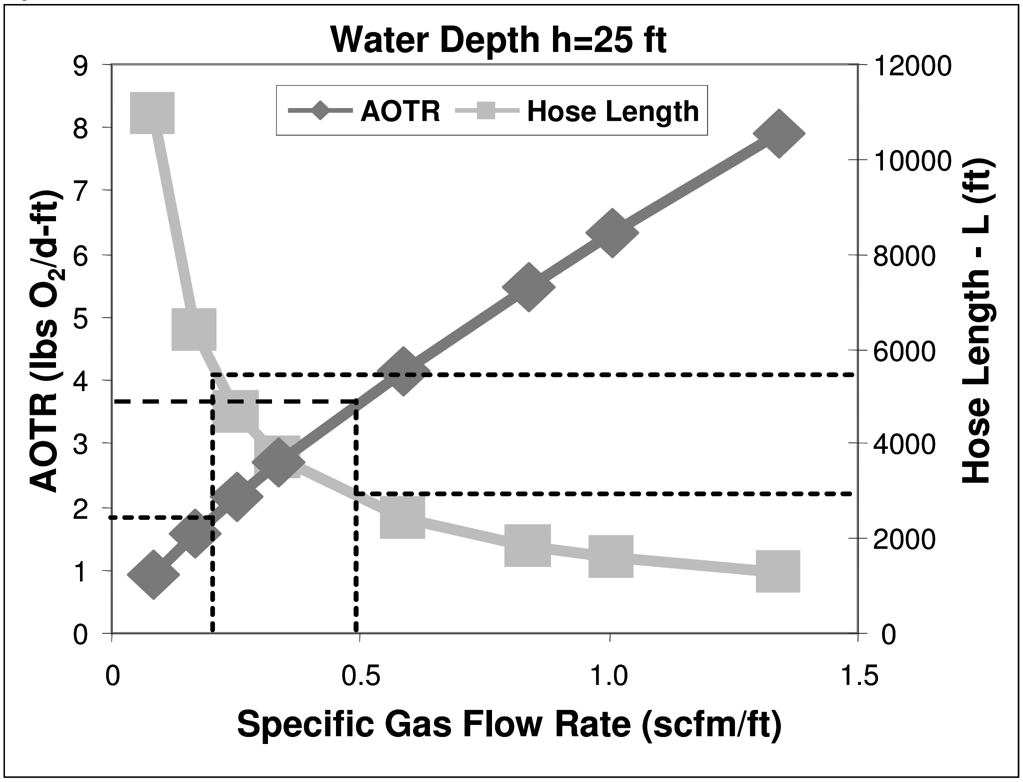
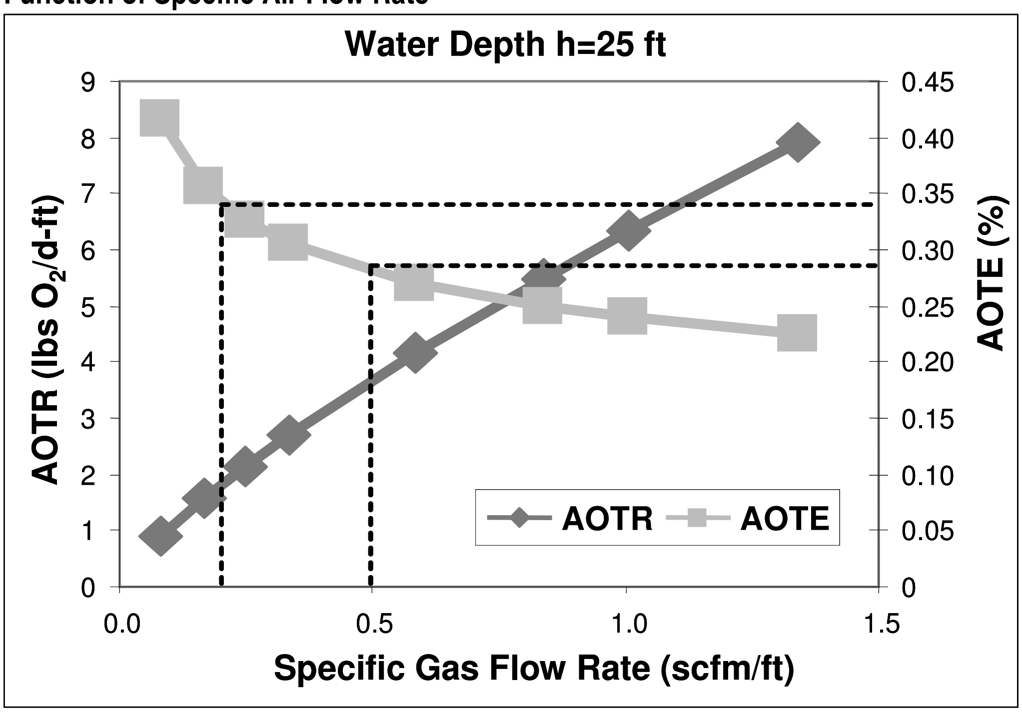



**Figure 39. Bubbler Hose Aeration Design Evaluation: Oxygen Transfer Rate and Efficiency as a Function of Specific Air Flow Rate**



Use Pure Oxygen

The oxygen transfer rates and efficiency and the length of hose needed to meet the design goal were evaluated for an operational water depth of 20 and 25 feet. The actual oxygen transfer rate and the hose length required to transfer 10,000 lbs/d of oxygen is a function of the specific oxygen gas flow rate applied. As shown in Figure 40, at a water depth of 20 feet, the specific AOTR (lbs/d-ft-length hose) ranges from 4.5 to 10.5 lbs/d-ft at specific air flow rate from 0.05 to 0.15 scfm-ft. The hose length needed is then estimated to be between 1,050 and 2,300 feet.

**Figure 40. Bubbler Hose Aeration Model Results: AOTR and Hose Length Required as a Function of Specific Gas Flow Rate, Use Oxygen**

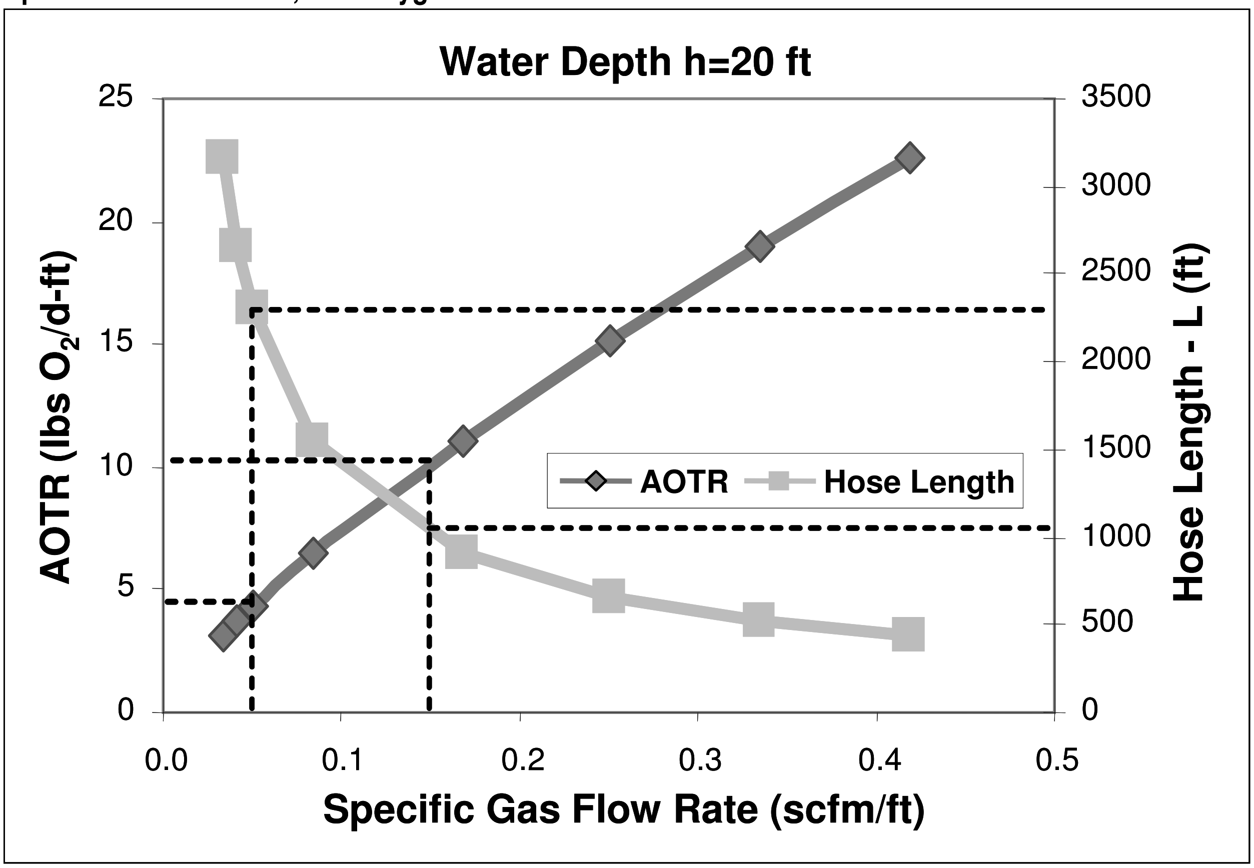



Figure 41 shows that the oxygen transfer efficiency decreases as the oxygen gas flow rate increases. At a specific oxygen gas flow rate of 0.05 to 0.15 scfm/ft, the oxygen transfer efficiency is only about 55 to 68 percent.

**Figure 41. Bubbler Hose Aeration Design Evaluation: Oxygen Transfer Rate and Efficiency as a Function of Specific Air Flow Rate**

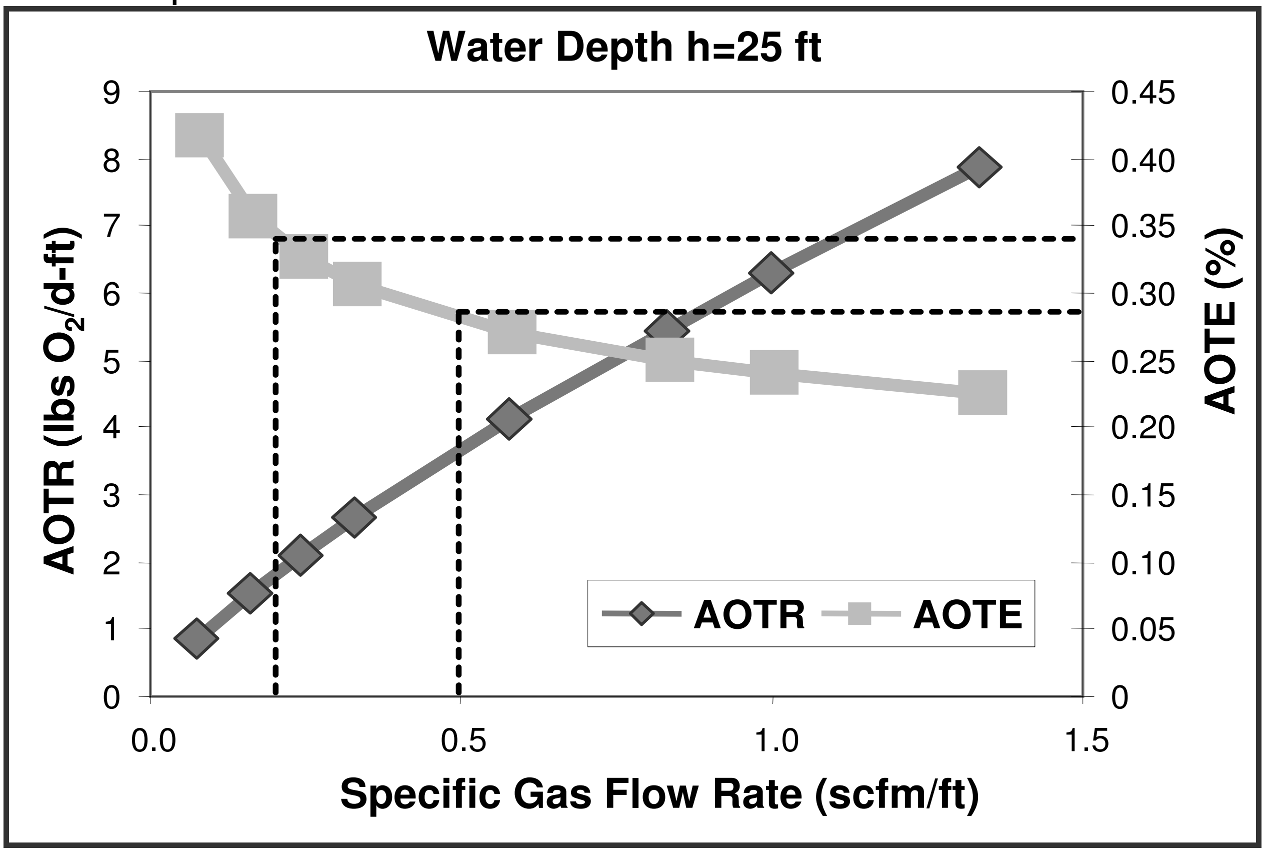



Figure 42 and Figure 43 show the similar oxygen transfer rate and efficiency as a function of specific oxygen gas flow rates at a water depth of 25 feet. Both the oxygen transfer rate and efficiency increases as water depth increases. At a specific oxygen gas flow rate of 0.05 to 0.15 scfm/foot, 800 to 1,900 feet of hose would be required to deliver 10,000 lbs/d of oxygen at a rate of 5.5 to 12.5 lbs/d-ft-length hose. At this operational condition, the oxygen transfer efficiency is about 65 to 82 percent. This is higher than the efficiency at 20 feet of 55 to 68 percent.

**Figure 42. Bubbler Hose Aeration Model Results: AOTR and Hose Length Required as a Function of Specific Gas Flow Rate, use Oxygen**

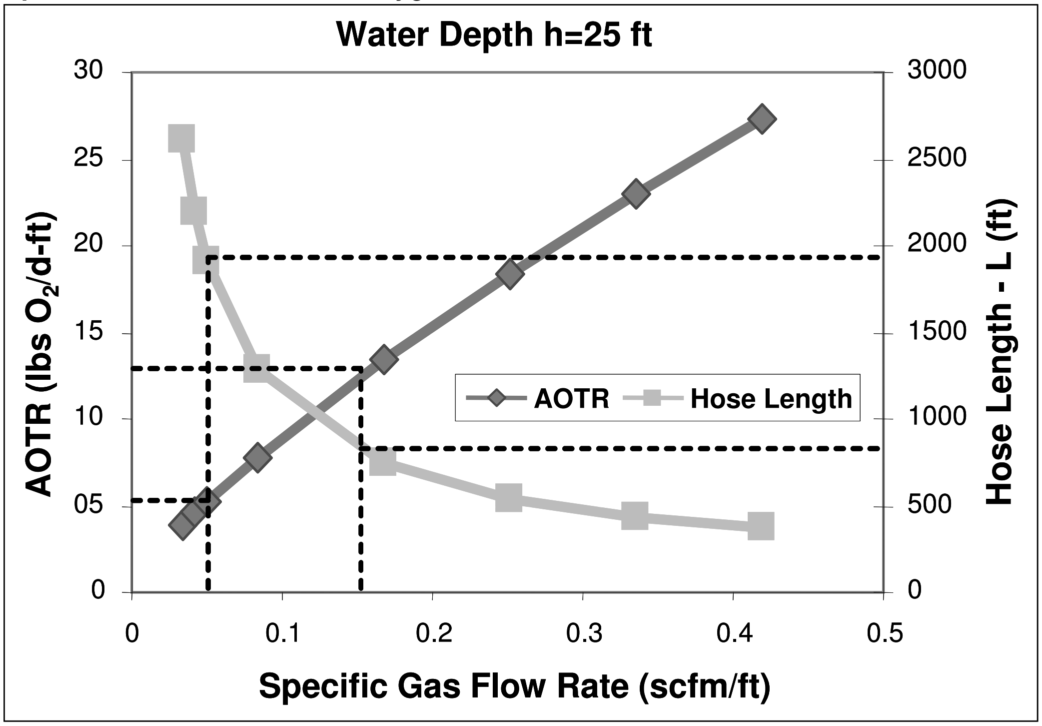
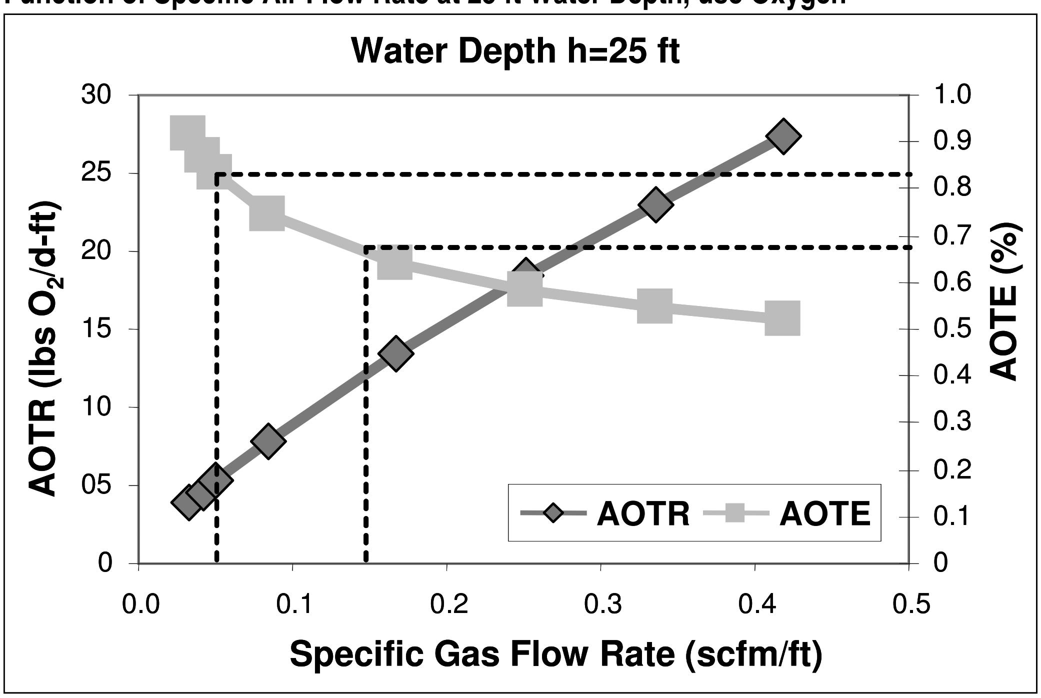



**Figure 43. Bubbler Hose Aeration Design Evaluation: Oxygen Transfer Rate and Efficiency as a Function of Specific Air Flow Rate at 25 ft Water Depth, use Oxygen**



## Summary of Evaluation Results

Alternative configurations were evaluated by varying the gas source (compressed air or pressurized oxygen), depth of diffuser placement in the water, and gas flows. All alternatives were configured to meet the required 10,000 lbs/d design objective. After investigating these operation and configuration parameters that affect Bubble Plume aerator oxygen transfer performance, four configuration alternatives were selected for further cost and physical constraints evaluation. The four Bubble Plume aeration configuration alternatives are summarized in Table 22. A brief discussion of each alternative configuration is presented in the following paragraphs.

**Table 22. Final Design Criteria for Bubble Plume Alternatives**

| | | Symbol | Unit | A | B | C | D |
|---|---|---|---|---|---|---|---|
| | | | | Air | | Oxygen | |
| Configuration | Hose Length required | L | (ft) | 5500 | 3000 | 1900 | 800 |
| | Total Air (or Oxygen) Flow Requirement | $Q_a$ | scfm | 1100 | 1500 | 95 | 120 |
| Operational Condition | Water Depth | h | (ft) | 25 | 25 | 25 | 25 |
| | Temperature | T | °F | 82.4 | 82.4 | 82.4 | 82.4 |
| | Gas Flow Rate | $Q_g$ | scfm/ft | 0.2 | 0.5 | 0.05 | 0.15 |
| | Average Saturation DO at Middle Water Depth | $C_{sat}$ (ave) | mg/L | 11 | 11 | 52 | 52 |
| Oxygen Transfer Performance | Actual Oxygen Transfer Rate at Operation Condition | AOTR | lbs/d-ft | 1.5 | 3.6 | 5.5 | 12.5 |
| | Actual Oxygen Transfer Efficiency | AOTE | % | 34 | 28 | 82 | 65 |
| Power Requirements | | kW | kW | 35 | 65 | NA | NA |
| | | hp | hp | 47 | 87 | NA | NA |
| Annual Oxygen Cost (in thousands) | | $ | $US | NA | NA | $85.4 | $107.7 |
| Construction Cost (in millions) | | $ | $US | $ 2.86 | $ 1.82 | $ 0.95 | $ 0.47 |
| Annual O&M Costs (in thousands) | | $ | $US | $ 215 | $ 136 | $ 218 | $ 178 |
| Field Data Available | | | | Yes | Yes | Yes | Yes |

### *Alternative Configuration A*

Configuration A uses compressed ambient air as an oxygen source. At an effective application rate of 0.2 scfm/ft of bubble hose, 10,000 lbs/d of oxygen can be transferred into the DWSC at an estimated transfer efficiency of 34 percent given optimal oxygen transfer conditions within the DWSC. The resulting hose length required is therefore estimated to be 5,500 feet. A 50 horsepower compressor would be needed to deliver the required 1,100 scfm to the system.

#### *Alternative Configuration B*

Configuration B illustrates the effect of increasing the effective application from 0.2 scfm/ft to 0.5 scfm/ft of bubble hose. The resulting change in oxygen transfer efficiency drops from 34 percent to an estimated 28 percent. However, because the oxygen transfer rate increases per unit foot of bubble hose, only 3,000 feet of bubble hose is required. To deliver the required 1,500 scfm of ambient air to the bubble hose, a 75 horsepower compressor would be required. The associated energy costs therefore increase by approximately $71,000. But due to the decreased linear footage of bubble hose required, both capital and total annual O&M costs decrease.

#### *Alternative Configuration C*

Pure oxygen gas is used in Configuration C to deliver the targeted 10,000 lbs/d of oxygen. This configuration assumes an effective application rate of 0.05 scfm/ft of BIOX™ hose to achieve an oxygen transfer efficiency of 85 percent (based upon manufacturer specs and adjusted for the conditions within the DWSC). The total oxygen feed rate to the system would therefore be 95 scfm when delivered to 1,900 feet of bubble hose. The oxygen would be supplied from a 9,000 gallon pressurized storage tank and would not require compressor or blower equipment. Actual oxygen transfer rates realized in an open column system such as the DWSC are expected to be less than 85 percent. However, due to the lack of actual field testing data for the BIOX hose, the actual adjustment for transfer efficiency within the DWSC is relatively unknown. Due to the very high oxygen transfer expectations of this hose type, it is recommended that field testing be conducted at a pilot scale level to verify actual oxygen transfer rates prior to full installation.

#### *Alternative Configurations D*

Configuration D uses data obtained from fine porous bubble hose manufacturers other than the manufacturer of BIOX mentioned above. The oxygen transfer efficiencies recommended for Configuration D are closely inline with industry standards for fine bubble systems using pure oxygen. This configuration assumes an effective oxygen application rate of 0.15 scfm/ft of bubble hose. Thus, 120 scfm of pure oxygen is delivered to 800 feet of hose at an estimated oxygen transfer efficiency of 65 percent. Like that of Configuration C, oxygen would be supplied from a 9,000 gallon pressurized storage tank and would not require compressor or blower equipment.

### Performance Conclusions

Conclusions developed from the Bubble Plume alternative evaluation suggest the following:

1. As expected, oxygen transfer efficiency increases with: increased water depth, decreased gas flow rate, and decreased bubble size.
2. Capital and total annualized costs are less for systems that use pure oxygen.
3. For this study, annual O&M costs are similar for both air and pure oxygen systems.

## Recommended Bubble Plume Configuration

All the alternatives provide sufficient oxygen transfer capacity to meet the performance criteria of 10,000 lbs/d. The major advantages of using pure oxygen include the fact that a blower and/or compressor is not required since the pure oxygen supply is already under pressure and a shorter diffuser lateral is needed to meet the required oxygen transfer rate. Both advantages result in overall cost and energy savings. Thus, Bubble Plume Configuration D was selected for further evaluation. Many of the operational and performance objectives can be met with the proper execution of an effective monitoring program.

### *Implementation*

Implementation of the Bubble Plume system includes the installation of an oxygen source, a delivery system, and the bubble hose diffusers. For this configuration, the oxygen source consists of a 9,000 gallon oxygen storage tank to be installed on the bank of the DWSC. An oxygen supply line transports pure oxygen gas from the tank, through the oxygen control equipment, and delivers it to an 800 foot oxygen distribution line. Laterals from the distribution line supply oxygen to the 800 feet of bubble hose at regular intervals so the equal distribution is obtained. Pressure regulating stations can be constructed in-line with the distribution line to equalize pressure throughout the system, ensuring even dispersal of bubbles into the receiving water. The pressure regulating stations can also be used to isolate certain areas of the bubbler hose and/or direct oxygen to certain areas. A plan for Bubble Plume installation is shown in Figure 44.

### *Design Elements*

The specific design elements associated with the recommended Bubble Plume configuration are described in

Table 23.

**Figure 44. Bubble Plume Installation Plan**

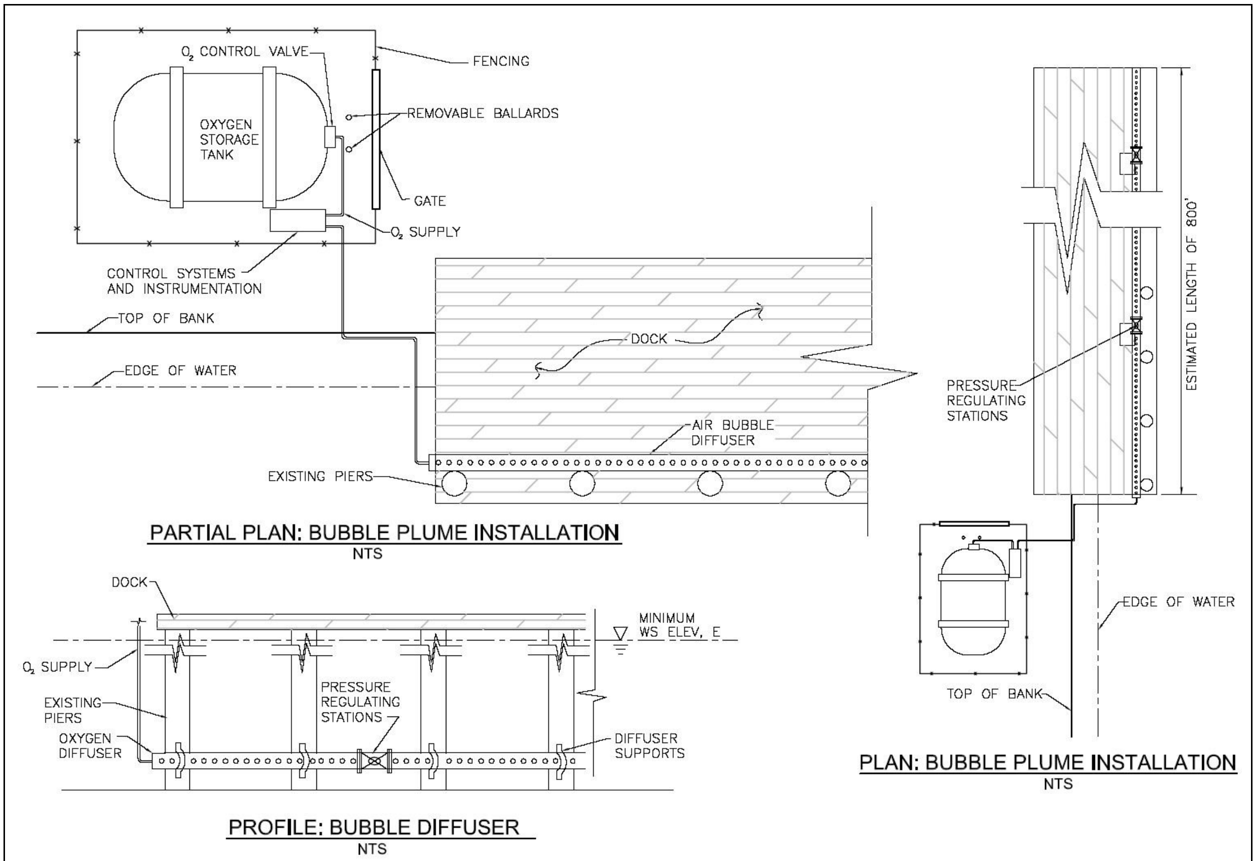



**Table 23. Summary of Bubble Plume Design Elements**

| Design Element | Description |
|---|---|
| *Site Work* | |
| Foundations and Slabs | Concrete foundations are required for the 9,000-gallon oxygen supply tank. The slab for the 9,000-gallon oxygen storage tank must be at least 20 feet long by 12 feet wide. An additional 12 x 12-foot slab is required near the oxygen control and refilling equipment. |
| Pavement | Six inches of aggregate base below 3 inches of asphaltic concrete shall provide a clean, orderly, and drivable working area surrounding the oxygen storage facility. A 30 x 30-foot paved area is required. |
| Fencing | Chain link fencing is used to enclose and secure the pump facility housing and oxygen supply equipment. At least 120 feet of 8-foot-high fencing is required. One 12-foot gate can be installed to allow for entry of personnel and vehicles. |
| *General Equipment* | |
| Bubble Hose | At least 800 feet of fine porous bubble hose will be used to diffuse oxygen into the DWSC. Several manufacturers, diameters, and types are available. |

| Design Element | Description |
|---|---|
| *Mechanical* | |
| Oxygen Distribution Line | An oxygen distribution line should run parallel to the bubble hose in order to equally distribute oxygen throughout the system. |
| Pressure Regulating Stations | Pressure regulating stations/valves can be used to equalize pressure within the oxygen distribution system. These valve stations can be used to ensure equal gas emission across the entire Bubble Plume system or to direct oxygen gas to specific areas within the 800 feet reach of bubble hose. Regulating stations are controlled by the electronic control equipment and programming located with the pump facility housing. They can be controlled via radio transmission or by wire feed. |
| *Oxygen Supply* | |
| Oxygen Storage Tank | A 9,000-gallon storage tank shall be provided and installed by a commercial oxygen supplier. Oxygen storage equipment is available on a monthly rental basis. |
| Oxygen Control and Supply Equipment | Electronic instrumentation and an oxygen gas control valve shall be used to measure and control oxygen supply rates to the system. |

## Summary of Selected Alternatives

The results of the technology evaluation suggest that all three technologies are applicable for the specific conditions and goals of this Engineering Feasibility Study. Thus, as described above, the three candidates for installation include:

- Alternative 1: U-Tube Configuration A
- Alternative 2: Speece Cone Configuration A
- Alternative 3: Bubble Plume Configuration D

These three technologies are further summarized, evaluated, and compared in the following Alternative Comparison.

# Alternative Comparison

The three selected alternatives were evaluated and their specific costs and performance data compared. The evaluation process included: 1) the development of selection criteria, and 2) evaluation of each alternative based upon each selection criteria. This evaluation process is described below.

## DEVELOPMENT OF SELECTION CRITERIA

A list of selection criteria was developed by HDR, JSA, DWR, and RWQCB. Each criterion addresses the major considerations associated with implementation, impacts, and performance of each alternative. Alternatives were evaluated by quantifying how well they met each of the following selection criteria:

- O&M Costs
- Total Annualized Costs
- Oxygen Transfer Efficiency
- Energy Consumption
- Maturity of Technology
- Flexibility

The specific definition of each selection criteria are explained further in the following Alternative Comparison section.

## ALTERNATIVE COMPARISON

The selected configuration for each technology was evaluated giving consideration to each selection criteria presented above. Where applicable data, calculations, and or values are available, a quantitative comparison is made. In this case, conclusions can be drawn from the tables of data provided for each evaluated technology. Quantitative data is available for O&M Costs, Total Annualized Costs, Oxygen Transfer Efficiency, and Energy Consumptions.

For those selection criteria that are not based upon quantitative data, a qualitative discussion is provided. These selection criteria include Maturity of Technology and Flexibility. A summary of the alternative comparison for each selection criteria is presented in the following paragraphs.

### Operation and Maintenance Costs

Preliminary O&M cost opinions were used to rate the alternatives. The cost opinions included items such as labor, routine maintenance, energy requirements, special personnel, oxygen costs, tank rental, and special programs. A summary of associated annual O&M costs is provided in Table 24. Detailed spreadsheets summarizing operation cost opinion development are provided in Appendix A.

**Table 24. Summary of Estimated Annual O&M Costs.**

| Alternative | US$ |
|---|---|
| **Alternative 1: U-Tube A** | |
| Equipment Maintenance (Equipment and Mechanical) | $ 12,660 |
| Monitoring and Adaptive Management | $ 37,100 |
| Oxygen Tank Rental | $ 9,000 |
| Oxygen Supply | $ 75,600 |
| Power Costs | $ 2,370 |
| Rounded Total | $ 137,000 |
| **Alternative 2: Speece Cone A** | |
| Pump Maintenance | $ 2,300 |
| Pipe Maintenance | $ 2,600 |
| Monitoring and Adaptive Management | $ 37,500 |
| Oxygen Tank Rental | $ 9,000 |
| Oxygen Supply | $ 93,340 |
| Power costs | $ 6,450 |
| Rounded Total | $ 152,000 |
| **Alternative 3: Bubble Plume D** | |
| Equipment Maintenance (Equipment and Mechanical) | $ 46,500 |
| Monitoring and Adaptive Management | $ 13,950 |
| Oxygen Tank Rental | $ 9,000 |
| Oxygen Supply | $ 107,695 |
| Rounded Total | $ 178,000 |

## Annualized Cost

Annualized costs were rated by the number of lbs/d of oxygen transferred. Construction and other costs were converted to present values and then amortized at 5.625 percent interest over the project design life of 20 years. It is assumed that each alternative is used to its target potential, imparting 10,000 lbs/d for 100 days of oxygen into the DWSC. Costs considered in this evaluation include:

- First Capital Costs with 35 percent Contingency
- Reoccurring Capital Expenditures
- O&M Costs

The basis of opinion of probable costs for each alternative is presented in Appendix A. Salvage cost at the end of the projected design life is not included in cost calculations. Table 25 summarizes the major cost elements for the three selected alternatives.

**Table 25. Summary of Major Cost Elements***

| Alternative | First Capital Cost | Present Value Reoccurring Costs | Annual O&M Costs | Combined Annualized Cost | Annual Cost per Pound $O_2$ |
|---|---|---|---|---|---|
| 1 - U-Tube A | $1,855,000 | $69,000 | $137,000 | $300,000 | 0.30 |
| 2 - Speece Cone A | $1,875,000 | $71,000 | $152,000 | $317,000 | 0.32 |
| 3 - Bubble Plume D | $465,000 | $98,000 | $178,000 | $226,000 | 0.23 |
| *Costs in $US | | | | | |

## Oxygen Transfer Efficiency

The oxygen transfer efficiency of the three alternatives ranged from 65 to 95 percent. A summary of the oxygen transfer efficiencies for each alternative is presented in Table 26.

**Table 26. Summary of Oxygen Transfer Efficiency**

| Alternative | Efficiency % |
|---|---|
| 1: U-Tube-A | 92 |
| 2: Speece Cone-A | 84 |
| 3: Bubble Plume-D | 65 |

The evaluation and conclusions associated with these oxygen transfer efficiencies are discussed in detail in the previous Technology Evaluation section.

## Energy Consumption

Energy consumption incorporates the total power (hp) and annual kWh requirements of the alternative to meet the selected operational goal of oxygen transfer of 10,000 lbs/d and 1,000,000 lbs/year. A summary of the energy consumption associated with each alternative is presented in Table 27.

**Table 27. Summary of Energy Consumption**

| Cost Element | Unit | U-Tube A | Speece Cone A | Bubble Plume D |
|---|---|---|---|---|
| Annual Energy Consumption | kWh | 39,400 | 107,400 | Control Only |
| Associated Annual Energy Cost | $US | 2,370 | 6,450 | N/A |

The evaluation and conclusions associated with energy consumption are discussed in detail in the previous Technology Evaluation section.

## Maturity of Technology

Alternatives were evaluated based upon the availability of empirical data and proven design criteria, as well as the estimated number of known applications. The rational for the selection of the alternative ratings is summarized in the following paragraphs.

### *Alternative 1: U-Tube A*

Through research and data collection, it is apparent that the U-Tube technology is not widely used. Applications of the U-Tube are currently limited to oxygenation of industrial process water and of recycled water used for fish farming facilities, therefore empirical data is limited. However, field data is available for a U-Tube configuration very similar to the one proposed as Alternative 1. In this case, empirical data collected during U-Tube operation has shown that the U-Tube is a promising and efficient technology that is very applicable to this project.

### *Alternative 2: Speece Cone A*

Research and data collection revealed that the Speece Cone has been tested and implemented in several locations. Each configuration, however, is very dissimilar to the potential application of this alternative within the DWSC. In most cases, the Speece Cone relies on the hydrostatic pressure created by deep deployment 100 to 300 feet below the water surface. There is some uncertainty in the assumptions used to extrapolate configuration and operational parameters for the design models developed as part of this study.

### *Alternative 3: Bubble Plume D*

Bubble Plume aeration and oxygenation systems have been studied in depth and have been field-tested through many real applications for several decades. This technology is highly developed. As such, configuration and operational parameters are readily available through industry literature and from manufactures. Diffuser options, construction materials, and troubleshooting techniques are readily available.

## Flexibility

The flexibility of each technology was evaluated based upon its ability to meet project objectives under a variety of environmental and operational conditions. Such environmental conditions may include temperature variations, flow variations, water depth variations, and the presence of obstacles such as large ships blocking diffuser equipment. Operation considerations include the ability of the alternative to meet higher or lower daily transfer rates or the ability of an alternative to maintain stable reliable levels of performance.

### *Alternative 1: U-Tube A*

Due to the fact that pure oxygen gas is used as an oxygen source, the driving force of oxygen to dissolve in water will remain high over a wide range of temperatures and initial DO concentrations. This is due to the high saturation concentration of pure oxygen in water rather than the oxygen from ambient air in water.

The ability of the U-Tube Alternative to meet high levels of performance over a range of operational conditions is greater than the other alternatives evaluated. Primarily and most importantly, for the selected U-Tube configuration, the U-Tube performance is expected to remain relatively stable over the calibrated range of conditions evaluated with this study. Although oxygen transfer efficiency may change when, for example, gas and water flow rates are modified, as long as certain minimum requirements are met, it is expected to perform reasonably well compared to the other two alternatives. In addition, the two pump and two U-Tube configuration will further increase the flexibility in meeting operational objectives. Half of the design oxygen transfer capacity can be transferred easily by only operating one pump.

Considerations for navigation obstacles were added into the conceptual design of the diffuser that will be used to disperse oxygenated water to the receiving waterbody. As mentioned previously, pressure regulating stations/valves can be used ensure equal dispersal across the entire diffuser system or to direct oxygenated water to specific areas within the 800 feet reach of diffuser.

### *Alternative 2: Speece Cone A*

The use of pure oxygen gas as an oxygen source has the same advantages that were mentioned for the U-Tube. The driving force of oxygen to dissolve in water will remain high over a wide range of temperatures and initial DO concentrations.

However, unlike the U-Tube, the Speece Cone performance is much more sensitive to operational changes. The evaluation conducted during the technology evaluation suggests that oxygen transfer efficiencies within the Speece Cone can differ greatly when gas or liquid flow rates are altered. This is primarily due to the fact that oxygen transfer efficiencies within the Speece Cone are highly dependant upon residence time and the position of the gas trap. When operational parameters are altered, not only does the residence time change, but the position of the gas trap changes as well. This has a significant effect on the oxygen transfer efficiency.

Flexibility will be greater due to use of two pumps and two Speece Cones, similar to the U-Tube configuration.

The Speece Cone alternative employs the same ideas for dispersing oxygenated water in the receiving waterbody, as does the U-Tube. Thus, both alternatives have the flexibility of focusing water dispersal to one area or another along the diffuser system.

### *Alternative 3: Bubble Plume D*

The use of pure oxygen gas as an oxygen source has the same advantages that were mentioned for the two alternatives. The driving force of oxygen to dissolve in water will remain high over a wide range of temperatures and initial DO concentrations.

The primary disadvantage of the Bubble Plume system is the potential for fouling along the entire length of hose either due to biological growth or from the scaling of various salts present within the water. Performance of Bubble Plume systems have shown to degrade quickly over time as the system is used and even quicker if the system is not used. General maintenance, cleaning, and replacement of bubble hose sections must be conducted in order to maintain expected levels of performance.

This alternative employs the same ideas for dispersing oxygen gas into the receiving waterbody, as does the previous two alternatives for oxygenated water. Thus, all alternatives have the flexibility of focusing dispersal to one area or another along the diffuser system to avoid the potential impedance by the presence of large ships.

## SUMMARY OF ALTERNATIVES

Table 28 summarizes the results of the alternative evaluation and comparison for the three alternatives.

**Table 28. Summary of Alternatives**

| Selection Criteria | Alternative 1 | Alternative 2 | Alternative 3 |
|---|---|---|---|
| Annual O&M Costs | $ 137,000 | $ 152,000 | $ 178,000 |
| Total Annualized Cost | $ 0.30 /lb $O_2$ | $ 0.32 /lb $O_2$ | $ 0.23 /lb $O_2$ |
| Oxygen Transfer Efficiency | 92% | 84% | 65% |
| Energy Consumption | 39,400 kWh | 107,400 kWh | Control |
| Maturity of Technology | Moderate | Low | High |
| Flexibility | High | Low | Moderate |

### Technology Selection and Further Evaluations

With the data presented within this Engineering Feasibility Study, it is anticipated that input from DWR, CBDA, and RWQCB regarding the selection criteria could further refine the alternative selection process. For example, assigning weight or priority to certain criteria would influence the selection outcome, and therefore could result in a change in final prioritization. For example, should the annualized capital costs or maturity of technology criteria be weighted more heavily than the O&M costs, Alternative 3 could be ranked higher than Alternative 1. Conversely, if O&M costs were weighted more heavily than other criteria, the advantage of Alternative 1 over Alternatives 2 and 3 would be more distinctive.

Further, several assumptions made for the purposes of alternative evaluation should be tested and verified in the field. This may be conducted as part of a small scale pilot study prior to implementation or may be conducted through monitoring and adaptive management of the full scale system. Data obtained through a small scale pilot study may be used in the final design process to refine design elements and/or improve confidence in technology performance.

# References

Brown and Caldwell, (1995). “Comanche Reservoir Oxygenation System Demonstration Project: Report on Operation 1993/94.” Prepared for East Bay Municipal Utility District. December 1995.

DeMoyer, Connie D., John S. Oliver, and Steven C. Wilhelms, (2001). "Comparison of Submerged Aerator Effectiveness." *Journal of Lake and Reservoir Management*. v17p139-152.

Dryden, Dr. Howard T. Dryden Aqua Ltd. Phone and e-mail communication. June 21, 2004

Environmental Protection Agency, (1998). “Design Manual: Fine Pore Aeration Systems.” Prepared by the Center for Environmental Research Information. EPA/625/1-89/023 September 1998.

The Federal Office of Management and Budget, (2004). Annually prescribed discount rate for evaluating public infrastructure projects.

Foe, Gowdy, and McCarthy, (2002). “Draft Strawman Source and Linkage Analysis for Low DO in the Stockton Deepwater Ship Channel.” April 2002.

Fynes, Jim. MG Industries. Phone Conversation and e-mail communication. June 9, 2004

Gowdy, Mark, and Grober, Leslie, Total Maximum Daily Load for Low DO in the San Joaquin River, June 2003.

HDR, (2001). “Water Quality Improvement Project Phase 1 Final Report: Causes and Solutions.” Prepared for the City of Stockton. October 2001.

HDR, (2003). “Stockton Channel Water Quality Improvement Project: Technical Memorandum Results and Findings of Pilot Investigation Final Report.” Prepared for the City of Stockton. June 2003.

JSA, (2003).”Evaluation of Aeration Technology for the Stockton Deep Water Ship Channel.” Prepared for the California Bay-Delta Authority. January 2003.

JSA, (2004). “Aeration Research and Implementation Analysis Study for the Stockton Deep Water Ship Channel.” Prepared for the California Bay-Delta Authority. January 2004.

Lee, Fred and Anne Jones-Lee, (2003). “Synthesis and Discussion and Findings on the Causes and Factors Influencing Low DO in the San Joaquin River Deep Water Ship Channel near Stockton, California: Including 2002 Data.” March 2003.

McGinnis, Daniel F. and John C. Little, (1998). “Bubble Dynamics and Oxygen Transfer in a Speece Cone.” Water Science and Technology. Vol. 37, No. 2, pp 285-292.

National Marine Fisheries Service. (1997). "Fish Screening Criteria for Anadromous Salmonids". January 1997.

Regional Water Quality Control Board (RWQCB), (1998). "The Sacramento River and San Joaquin River Basin Water Quality Control Plan." Prepared by the California Regional Water Quality Control Board Central Valley Region, Fourth Edition.

Regional Water Quality Control Board, (2003). "Staff Report of the Total Maximum Daily Load for Low Dissolved Oxygen in the San Joaquin River." Prepared for the State of California, California environmental Protection Agency. June2003.

Rogers, Gary Ph.D, P.E. Aquatic Eco-Systems, Inc. Phone and e-mail communication. June 22, 2004.

Speece, R. E., 1990. "Summary of Test Results on Pilot Oxygenation Cone at Logan Martin Dam." Prepared for the Alabama Power Company. October 18, 1990.

Speece, R. E., (1993). "Field Test of Operational Performance of Naheola U-Tube Oxygenation System." Prepared for James River / Gulf States Paper Mills on the Tombigbee River. June 1, 1993.

Speece, R. E., (1996). "Oxygenation Supplementation by U-Tube to the Tombigbee River." *Water Science and Technology*, Vol. 34, No. 12, pp 83-90.

# Appendix A: Cost Data

A cost effectiveness analysis expresses the long-run cost of an alternative on a consistent basis using common benchmarks. For this Feasibility Study, the annualized sum of the capital and operations and maintenance (O&M) costs for each alternative were compared. The following procedure was used to determine the cost effectiveness of each alternative:

- Life-cycle costs for the project's capital, reoccurring, and O&M expenditures were developed using a 20-year project life.
- The total costs for each year were discounted to present-day (2004) dollars using a discount rate of 5.625 percent.
- The net present value of each alternative was calculated based on a 20-year project life and 5.625 percent discount rate.
- This net present value was then expressed on an annual basis by amortizing the value over 20 years at the above mentioned discount rate.

The baseline capital and O&M costs for each alternative were based on general project descriptions and the technical specifications presented in the Evaluation of Technologies section of the main report. Unit costs were determined based on previous cost estimates, several of which were obtained from projects located within the vicinity of the San Joaquin River. Other unit costs were obtained from vendors and other sources.

Several assumptions were made to extend the baseline costs over the life of the project. The main assumptions are as follows:

- Construction costs were grouped into a number of categories, including Site Work, Concrete, Masonry, Finishes, Equipment, Special Construction, Mechanical, and Electrical and Instrumentation. A number of project components will require replacement during the 20-year project life. It is assumed that the pump motor, impeller, and diffuser lateral pipe would each need replacement once, at 10 years of operation. The oxygen diffusers for the Speece Cone and U-tube would need to be replaced every 5 years.
- The total construction costs have a lump sum contingency of 35 percent. These fees apply to years during which construction or replacement occurs.
- Other project costs including engineering, permitting and construction services are included as percentages of Total Construction Costs (10 percent, 7 percent, and 10 percent respectively).
- Annual O&M costs include Equipment Maintenance, Monitoring and Adaptive Management, Oxygen Tank Supply (i.e., rental), Oxygen Supply and Power Costs. Equipment Maintenance and Monitoring and Adaptive Management were calculated as a percentage of the total estimated capital expenses (3 to 10 percent for Equipment Maintenance and 2 to 3 percent for Monitoring and Adaptive Management). Equipment Maintenance percentages were applied to the major mechanical and equipment components. Adaptive Management percentages are applied to the total capital cost of the project. Reoccurring capital expenses, such as replacements, are presented in an individual category and not lumped into Equipment Maintenance line items. Other items are calculated based on yearly cost per unit.
- Power costs were calculated by converting the horsepower (hp) for each alternative to kilowatts (kW), and assumed the device would operate 24 hours a day for 100 days.

## U-TUBE COSTS

The main difference in costs among Alternatives A through D is the cost of the vertical turbine pumps. This is due to the difference in hp requirements for either one or two U-tubes of different sizes. Different sizes of U-tubes requiring differing diameters of pipe connecting to the diffuser pipe. This diameter varies from 10 to 30 inches and thus, yields differing costs. The Mobilization/Demobilization costs for Alternative D are slightly higher compared to other alternatives due to costs associated with installation of the larger outer diameter of the connecting pipe. Replacement costs are the same for all alternatives. Power costs vary due to the differing requirements for each alternative; Alternative A is 22 hp (16.4 kW), Alternative B is 36 hp (26.8 kW), Alternative C is 45 hp (33.6 kW), and Alternative D is 100 hp. The costs of power for each alternative are summarized in Table A-1.

**Table A-1. Summary of U-Tube Power Costs.**

| U-Tube Alternative | Power (hp) | Power (kW) | Power Usage (kW-hr) | Annual Power Cost |
|---|---|---|---|---|
| A | 22 | 16.4 | 39,380 | $2,370 |
| B | 36 | 26.8 | 64,430 | $3,870 |
| C | 45 | 33.6 | 80,540 | $4,840 |
| D | 100 | 74.6 | 178,970 | $10,740 |

## SPEECE CONE COSTS

The main difference in Equipment costs for Alternatives A through C is the cost for the 60 hp vertical turbine pumps associated with Alternative A, the 240 hp pump for Alternative B, and the 690 hp pump for Alternative C. Power costs are presented below in Table A-2.

**Table A-2. Summary of Speece Cone Power Costs.**

| Speece Cone Alternative | Power (hp) | Power (kW) | Power Usage (kW-hr) | Annual Power Cost |
|---|---|---|---|---|
| A | 60 | 44.7 | 107,380 | $6,450 |
| B | 240 | 179.0 | 429,520 | $25,780 |
| C | 690 | 514.5 | 1,234,880 | $74,100 |

Costs for Alternative C are much higher than costs for Alternatives A and B due to the larger required pump and fish screen requirements.

## BUBBLE PLUME

The bubble plume alternatives can be divided into two categories, those using air and those using pure oxygen. Alternatives A and B which use air have power requirements, while Alternatives C and D run on pure oxygen and therefore do not require power. Alternative B requires almost twice the power as Alternative A. The additional cost is shown in Table A-3 below.

**Table A-3. Summary of Bubble Plume Power Costs.**

| Speece Cone Alternative | Power (hp) | Power (kW) | Power Usage (kW-hr) | Annual Power Cost |
|---|---|---|---|---|
| A | 47 | 35 | 62,640 | $4,000 |
| B | 87 | 65 | 116,330 | $6,980 |

The diffuser hose for Alternative A is almost twice as long as Alternative B with lengths of 11,000 and 6,000 feet respectively. The difference in length yields a much higher cost for Alternative A at $1,034,000 and Alternative B costing $564,000. However, for Alternatives C and D the costs are much lower ($22,800 and $9,600 for Alternative D) because of the shorter length requirements of 1,900 and 800 feet respectively.

The Annual Cost for each alternative was discounted to account for the "real" time value of money. The sum of the annual discounted costs over the 20-year life-cycle of the project was converted to the present value of the total cost over 20 years, including capital costs, O&M, and periodic replacements. This cost is summarized in Table A-4, followed by detailed cost sheets for each alternative.

**Table A-4. San Joaquin River Aeration Engineering Feasibility Study - Cost Summary.**

| Type | Alternative | Total Capital Costs | Present Value Recurring Expenses | Annual O&M Costs | Combined Annual Project Costs | Annual Cost Oxygen (per Unit) |
|---|---|---|---|---|---|---|
| U-Tube | A | $ 1,855,000.00 | $ 69,000.00 | $ 137,000.00 | $ 300,000.00 | $ 0.30 |
| | B | $ 1,996,000.00 | $ 69,000.00 | $ 143,000.00 | $ 318,000.00 | $ 0.32 |
| | C | $ 2,022,000.00 | $ 71,000.00 | $ 163,000.00 | $ 340,000.00 | $ 0.34 |
| | D | $ 2,823,000.00 | $ 133,000.00 | $ 223,000.00 | $ 473,000.00 | $ 0.47 |
| Speece Cone | A | $ 1,875,000.00 | $ 71,000.00 | $ 152,000.00 | $ 317,000.00 | $ 0.32 |
| | B | $ 2,041,000.00 | $ 69,000.00 | $ 160,000.00 | $ 339,000.00 | $ 0.34 |
| | C | $ 3,349,000.00 | $ 129,000.00 | $ 270,000.00 | $ 565,000.00 | $ 0.57 |
| Bubble Plume | A | $ 2,859,000.00 | $ 688,000.00 | $ 215,000.00 | $ 515,000.00 | $ 0.52 |
| | B | $ 1,818,000.00 | $ 379,000.00 | $ 136,000.00 | $ 322,000.00 | $ 0.32 |
| | C | $ 948,000.00 | $ 237,000.00 | $ 218,000.00 | $ 319,000.00 | $ 0.32 |
| | D | $ 465,000.00 | $ 98,000.00 | $ 178,000.00 | $ 226,000.00 | $ 0.23 |

Notes: Discount Rate = 0.05625

HDR | ONE COMPANY *Many Solutions*

**PRELIMINARY COST ESTIMATE**

## U-TUBE ALTERNATIVE A - TWO 2' OUTER DIAMETER (1' OUTER RADIUS) U-TUBES X 150 FT HEIGHT

**ENGINEER'S COST OPINION: PRELIMINARY DESIGN**
**CALIFORNIA BAY DELTA AUTHORITY**
**SAN JOAQUIN RIVER AERATION ENGINEERING FEASIBILITY STUDY**

**Construction Costs** **DATE: JULY 2, 2004** **CHD: JUL 6, 2004**

| Item | Description | | | Unit | Unit Price | Quantity | Item Price |
|---|---|---|---|---|---|---|---|
| **Division 1 - General Requirements** | | | | | | | |
| | | | | | | | |
| **Division 2 - Site Work** | | | | | | | |
| 1 | Cut/Fill | | | CY | $ 5 | 725 | $ 3,625 |
| 2 | Removable Bollards | | | EA | $ 300 | 6 | $ 1,800 |
| 3 | Fencing | | | LS | $ 6,500 | 1 | $ 6,500 |
| 4 | 6" AB | | | CY | $ 36 | 50 | $ 1,800 |
| 5 | 3" AC | | | SF | $ 5 | 1600 | $ 8,000 |
| **Division 3 - Concrete** | | | | | | | |
| 6 | $O_2$ Tank Slab | | | CY | $ 500 | 18 | $ 9,000 |
| 7 | Building Slab | | | CY | $ 500 | 10 | $ 5,000 |
| 8 | Wet Well | | | LS | $ 6,500 | 1 | $ 6,500 |
| **Division 4 - Masonry** | | | | | | | |
| 9 | Split-block Masonry Building (20' x 20') | | | SF | $ 250 | 400 | $ 100,000 |
| **10** | | | | | | | |
| 10 | Coatings | | | LS | $ 20,000 | 1 | $ 20,000 |
| **Division 11 - Equipment** | | | | | | | |
| 11 | Vertical Turbine Pumps and Appurtenances | | | EA | $ 26,800 | 2 | $ 53,600 |
| 12 | Drill & Prep 2' Diameter U-Tube Shaft | | | FT | $ 340 | 300 | $ 102,000 |
| 13 | U-Tube Casing Material (Assume Welded Steel, 1") | | | LB | $ 1 | 73,800 | $ 73,800 |
| 14 | Install U-Tube Casing | | | FT | $ 50 | 300 | $ 15,000 |
| 15 | Install Bottom Plug (concrete and mortar) | | | CY | $ 500 | 6 | $ 3,000 |
| 16 | Pump Water from Shaft and Prepare Casing | | | LS | $ 12,000 | 2 | $ 24,000 |
| 17 | Bubble Collector and Appurtenances | | | EA | $ 8,000 | 2 | $ 16,000 |
| 18 | Oxygen Diffuser | | | EA | $ 1,000 | 2 | $ 2,000 |
| 19 | Fish Screen (Barrel) | | | EA | $ 240,000 | 1 | $ 240,000 |
| **Division 13 - Special Construction** | | | | | | | |
| 20 | Pressure Gages/Transmitters | | | EA | $ 1,500 | 4 | $ 6,000 |
| 21 | Flow Meter (10" Mag) | | | EA | $ 13,500 | 2 | $ 27,000 |
| **Division 15 - Mechanical** | | | | | | | |
| 22 | $O_2$ Supply Line Piping and Appurtenances | | | LF | $ 12 | 200 | $ 2,400 |
| 23 | $O_2$ Control Valve and Equipment | | | EA | $ 3,000 | 2 | $ 6,000 |
| 24 | 10" Pump Control Valve | | | EA | $ 9,000 | 2 | $ 18,000 |
| 25 | Isolation Valves | | | EA | $ 3,000 | 3 | $ 9,000 |
| 26 | 16" Ductile Iron Pipe (Header) | $/Dia-In | 16 | LF | $ 144 | 20 | $ 2,880 |
| 27 | 10" Ductile Iron Pipe (Supply) | $/Dia-In | 10 | LF | $ 90 | 20 | $ 1,800 |
| 28 | 16" Ductile Iron Pipe (Exhaust) | $/Dia-In | 16 | LF | $ 144 | 40 | $ 5,760 |
| 29 | 16" Flexible Piping | $/Dia-In | 16 | LF | $ 144 | 60 | $ 8,640 |
| 30 | Inner Piping System (8 Inch) | $/Dia-In | 8 | LF | $ 72 | 300 | $ 21,600 |
| 31 | HDPE Diffuser Pipe (Assume 24" Dia) | $/Dia-In | 24 | LF | $ 18 | 800 | $ 14,400 |
| 32 | Pressure Regulating Station | | | EA | $ 8,000 | 4 | $ 32,000 |
| 33 | Diffuser Supports | | | EA | $ 150 | 80 | $ 12,000 |
| 34 | Lateral Installation | | | LF | $ 94 | 800 | $ 75,200 |
| **Division 16 - Electrical and Instrumentation** | | | | | | | |
| 35 | Supply | | | LS | $ 50,000 | 1 | $ 50,000 |
| 36 | Control Systems and Instrumentation | | | LS | $ 40,000 | 1 | $ 40,000 |
| 37 | Control Wiring | | | LS | $ 7,500 | 1 | 7,500 |
| **Rounded Subtotal*** | | | | | | | $ 1,032,000 |

| | | | | | |
|---|---|---|---|---|---|
| **General Contractor Indirect Costs** | | | | | |
| Construction Management (Contractor) | | | 2.5% | $ 1,032,000 | $ 25,800 |
| Mobilization/Demobilization | LS | $ 22,500 | | 1 | $ 22,500 |
| | | | Rounded Subtotal* | | $ 49,000 |
| | **Total Construction Costs** | | | | $ 1,081,000 |
| | Contingencies | | | **35%** | $ 378,350 |
| **TOTAL CONSTRUCTION COSTS WITH CONTINGENCIES*** | | | | | **$ 1,460,000** |
| **Other Project Costs** | | | | | |
| Engineering/SDC | | | | 10.0% | $ 146,000 |
| Permitting | | | | 7.0% | $ 102,200 |
| Construction Services/Inspections | | | | 10.0% | $ 146,000 |
| | | | Rounded Subtotal* | | $ 395,000 |
| **TOTAL ESTIMATED CAPITAL COSTS** | | | | | **$ 1,855,000** |
| **RECURRING CAPITAL EXPENSES** | **REPLACEMENT INTERVAL** | | | | |
| Pump Motor | 10 | yrs | | | $ 5,000 |
| Impeller | 10 | yrs | | | $ 5,000 |
| Diffuser Lateral | 10 | yrs | | | $ 101,600 |
| Oxygen Diffuser | 5 | yrs | | | $ 6,000 |
| **Total Recurring Capital Expenses** | | | Rounded Subtotal* | | **$ 118,000** |
| **ANNUAL OPERATIONS AND MAINTENANCE COSTS** | | | | | |
| Equipment Maintenance (Equipment and Mechanical) | | | | 3.0% | $ 12,660 |
| Monitoring and Adaptive Management | | | | 2.0% | $ 37,100 |
| Oxygen Tank Rental | Month | $ 750 | | 12 | $ 9,000 |
| Oxygen Supply (10,800 lbs/day) | lbs | $ 0.07 | | 1,080,000 | $ 75,600 |
| Power Costs | kW-hr | $ 0.06 | | 39,380 | $ 2,370 |
| **Total Annual O & M Costs*** | | | | | **$ 137,000** |

*Rounded up to the nearest $1,000.

HDR ONE COMPANY *Many Solutions*

**PRELIMINARY COST ESTIMATE**

## U-TUBE ALTERNATIVE B - ONE 3.5' OUTER DIAMETER (1.75' OUTER RADIUS) U-TUBE X 220 FT HEIGHT

**ENGINEER'S COST OPINION: PRELIMINARY DESIGN**
**CALIFORNIA BAY DELTA AUTHORITY**
**SAN JOAQUIN RIVER AERATION ENGINEERING FEASIBILITY STUDY**

**Construction Costs** **DATE: JULY 2, 2004** **CHD: JUL 6, 2004**

| Item | Description | | | Unit | Unit Price | Quantity | Item Price |
|---|---|---|---|---|---|---|---|
| **Division 1 - General Requirements** | | | | | | | |
| **Division 2 - Site Work** | | | | | | | |
| 1 | Cut/Fill | | | CY | $ 5 | 725 | $ 3,625 |
| 2 | Removable Bollards | | | EA | $ 300 | 6 | $ 1,800 |
| 3 | Fencing | | | LS | $ 6,500 | 1 | $ 6,500 |
| 4 | 9" AB | | | CY | $ 36 | 50 | $ 1,800 |
| 5 | 3" AC | | | SF | $ 5 | 1600 | $ 8,000 |
| **Division 3 - Concrete** | | | | | | | |
| 6 | $O_2$ Tank slab | | | CY | $ 500.0 | 18 | $ 9,000 |
| 7 | Building slab | | | CY | $ 500.0 | 10 | $ 5,000 |
| 8 | Wet Well | | | LS | $ 6,500.0 | 1 | $ 6,500 |
| **Division 4 - Masonry** | | | | | | | |
| 9 | Split-block Masonry Building (20' x 20') | | | SF | $ 250.0 | 400 | $ 100,000 |
| **Division 9 - Finishes** | | | | | | | |
| 10 | Coatings | | | LS | $ 20,000.0 | 1 | $ 20,000 |
| **Division 11 - Equipment** | | | | | | | |
| 11 | Vertical Turbine Pumps and Appurtenances | | | EA | $ 61,200 | 1 | $ 61,200 |
| 12 | Drill & Prep 3.5' Diameter U-Tube Shaft | | | FT | $ 720 | 220 | $ 158,400 |
| 13 | Casing Material (Assume Welded Steel, 1") | | | LB | $ 1 | 99,300 | $ 99,300 |
| 14 | Install U-Tube Casing | | | FT | $ 50 | 220 | $ 11,000 |
| 15 | Install Bottom Plug (concrete and mortar) | | | CY | $ 500 | 6 | $ 3,000 |
| 16 | Pump Water from Shaft and Prepare Casing | | | LS | $ 25,000 | 1 | $ 25,000 |
| 17 | Bubble Collector and Appurtenances | | | EA | $ 8,000 | 1 | $ 8,000 |
| 18 | Oxygen Diffuser | | | EA | $ 1,500 | 1 | $ 1,500 |
| 19 | Fish Screen (Barrel) | | | EA | $ 275,000 | 1 | $ 275,000 |
| **Division 13 - Special Construction** | | | | | | | |
| 20 | Pressure Gages/Transmitters | | | EA | $ 1,500 | 2 | $ 3,000 |
| 21 | Flow Meter (18" Mag) | | | EA | $ 16,800 | 1 | $ 16,800 |
| **Division 15 - Mechanical** | | | | | | | |
| 22 | $O_2$ Supply Line Piping and Appurtenances | | | LF | $ 12 | 100 | $ 1,200 |
| 23 | $O_2$ Control Valve and Equipment | | | EA | $ 3,000 | 1 | $ 3,000 |
| 24 | 18" Pump Control Valve | | | EA | $ 24,000 | 1 | $ 24,000 |
| 25 | Isolation Valves | | | EA | $ 6,000 | 2 | $ 12,000 |
| 26 | 18" Ductile Iron Pipe | $/Dia-In | 18 | LF | $ 162 | 40 | $ 6,480 |
| 27 | 18" Flexible Piping | $/Dia-In | 18 | LF | $ 162 | 60 | $ 9,720 |
| 28 | Inner Piping System (12 Inch) | $/Dia-In | 12 | LF | $ 108 | 220 | $ 23,760 |
| 29 | HDPE Diffuser Pipe (Assume 24" Dia) | $/Dia-In | 24 | LF | $ 18 | 800 | $ 14,400 |
| 30 | Pressure Regulating Station | | | EA | $ 5,000 | 4 | $ 20,000 |
| 31 | Diffuser Supports | | | EA | $ 150 | 80 | $ 12,000 |
| 32 | Lateral Installation (Within Water Column) | | | LF | $ 94 | 800 | $ 75,200 |
| **Division 16 - Electrical and Instrumentation** | | | | | | | |
| 33 | Supply | | | LS | $ 50,000 | 1 | $ 50,000 |
| 34 | Control Systems and Instrumentation | | | LS | $ 30,000 | 1 | $ 30,000 |
| 35 | Control Wiring | | | LS | $ 5,000 | 1 | 5,000 |
| **Rounded Subtotal*** | | | | | | | $ 1,112,000 |

**General Contractor Indirect Costs**

| | | | | |
|---|---|---|---|---|
| Construction Management (Contractor) | | 2.5% | $ 1,112,000 | $ 27,800 |
| Mobilization/Demobilization | LS | $ 22,500 | 1 | $ 22,500 |
| | | Rounded Subtotal* | | $ 51,000 |
| | **Total Construction Costs** | | | $ 1,163,000 |
| | Contingencies | | **35%** | $ 407,050 |
| **TOTAL CONSTRUCTION COSTS WITH CONTINGENCIES*** | | | | **$ 1,571,000** |

**Other Project Costs**

| | | | |
|---|---|---|---|
| Engineering/SDC | | 10.0% | $ 157,100 |
| Permitting | | 7.0% | $ 109,970 |
| Construction Services/Inspections | | 10.0% | $ 157,100 |
| | Rounded Subtotal* | | $ 425,000 |
| **TOTAL ESTIMATED CAPITAL COSTS** | | | **$ 1,996,000** |

| **RECURRING CAPITAL EXPENSES** | **REPLACEMENT INTERVAL** | | |
|---|---|---|---|
| Pump Motor | 10 | yrs | $ 5,000 |
| Impeller | 10 | yrs | $ 5,000 |
| Diffuser Lateral | 10 | yrs | $ 101,600 |
| Oxygen Diffuser | 5 | yrs | $ 4,500 |
| **Total Recurring Capital Expenses** | | Rounded Subtotal* | **$ 117,000** |

**ANNUAL OPERATION AND MAINTENANCE COSTS**

| | | | | |
|---|---|---|---|---|
| Equipment Maintenance (Equipment and Mechanical) | | | 3.0% | $ 14,780 |
| Monitoring and Adaptive Management | | | 2.0% | $ 39,920 |
| Oxygen Tank Rental | Month | $ 750 | 12 | $ 9,000 |
| Oxygen Supply (10,750 lbs/day) | lbs | $ 0.07 | 1,075,000 | $ 75,250 |
| Power Costs | kW-hr | $ 0.06 | 64,430 | $ 3,870 |
| **Total Annual O & M Costs*** | | | | **$ 143,000** |

*Rounded up to the nearest $1,000.

**PRELIMINARY COST ESTIMATE**

## U-TUBE ALTERNATIVE C - ONE 4' OUTER DIAMETER (2' OUTER RADIUS) U-TUBE X 165 FT HEIGHT

**ENGINEER'S COST OPINION: PRELIMINARY DESIGN**
**CALIFORNIA BAY DELTA AUTHORITY**
**SAN JOAQUIN RIVER AERATION ENGINEERING FEASIBILITY STUDY**
**DATE: JULY 2, 2004** **CHD: JUL 6, 2004**

**Construction Costs**

| Item | Description | | | Unit | Unit Price | Quantity | Item Price |
|---|---|---|---|---|---|---|---|
| **Division 1 - General Requirements** | | | | | | | |
| | | | | | | | |
| **Division 2 - Site Work** | | | | | | | |
| 1 | Cut/Fill | | | CY | $ 5 | 725 | $ 3,625 |
| 2 | Removable Bollards | | | EA | $ 300 | 6 | $ 1,800 |
| 3 | Fencing | | | LS | $ 6,500 | 1 | $ 6,500 |
| 4 | 9" AB | | | CY | $ 36 | 50 | $ 1,800 |
| 5 | 3" AC | | | SF | $ 5 | 1600 | $ 8,000 |
| **6** | | | | | | | |
| 6 | $O_2$ Tank slab | | | CY | $ 500.0 | 18 | $ 9,000 |
| 7 | Building slab | | | CY | $ 500.0 | 10 | $ 5,000 |
| 8 | Wet Well | | | LS | $ 6,500.0 | 1 | $ 6,500 |
| **Division 4 - Masonry** | | | | | | | |
| 9 | Split-block Masonry Building (20' x 20') | | | SF | $ 250.0 | 400 | $ 100,000 |
| **Division 9 - Finishes** | | | | | | | |
| 10 | Coatings | | | LS | $ 20,000.0 | 1 | $ 20,000 |
| **Division 11 - Equipment** | | | | | | | |
| 11 | Vertical Turbine Pumps and Appurtenances | | | EA | $ 76,500 | 1 | $ 76,500 |
| 12 | Drill & Prep 4' Diameter U-Tube Shaft | | | FT | $ 510 | 165 | $ 84,150 |
| 13 | Casing Material (Assume Welded Steel, 1") | | | LB | $ 1 | 82,900 | $ 82,900 |
| 14 | Install U-Tube Casing | | | FT | $ 50 | 165 | $ 8,250 |
| 15 | Install Bottom Plug (concrete and mortar) | | | CY | $ 500 | 8 | $ 4,000 |
| 16 | Pump Water from Shaft and Prepare Casing | | | LS | $ 12,000 | 1 | $ 12,000 |
| 17 | Bubble Collector and Appurtenances | | | EA | $ 8,000 | 1 | $ 8,000 |
| 18 | Oxygen Diffuser | | | EA | $ 2,000 | 1 | $ 2,000 |
| 19 | Fish Screen (Barrel) | | | EA | $ 357,500 | 1 | $ 357,500 |
| **Division 13 - Special Construction** | | | | | | | |
| 20 | Pressure Gages/Transmitters | | | EA | $ 1,500 | 2 | $ 3,000 |
| 21 | Flow Meter (12" Mag) | | | EA | $ 13,500 | 1 | $ 13,500 |
| **Division 15 - Mechanical** | | | | | | | $ 16,500 |
| 22 | $O_2$ Supply Line Piping and Appurtenances | | | LF | $ 12 | 100 | $ 1,200 |
| 23 | $O_2$ Control Valve and Equipment | | | EA | $ 3,000 | 1 | $ 3,000 |
| 24 | 18" Pump Control Valve | | | EA | $ 24,000 | 1 | $ 24,000 |
| 25 | Isolation Valves | | | EA | $ 11,000 | 2 | $ 22,000 |
| 26 | 18" Ductile Iron Pipe | $/Dia-In | 18 | LF | $ 162 | 20 | $ 3,240 |
| 27 | 18" Flexible Piping | $/Dia-In | 18 | LF | $ 162 | 60 | $ 9,720 |
| 28 | Inner Piping System (18 Inch) | $/Dia-In | 18 | LF | $ 162 | 165 | $ 26,730 |
| 29 | HDPE Diffuser Pipe (Assume 24" Dia) | $/Dia-In | 24 | LF | $ 18 | 800 | $ 14,400 |
| 30 | Pressure Regulating Station | | | EA | $ 5,000 | 4 | $ 20,000 |
| 31 | Diffuser Supports | | | EA | $ 150 | 80 | $ 12,000 |
| 32 | Lateral Installation (Within Water Column) | | | LF | $ 94 | 800 | $ 75,200 |
| **Division 16 - Electrical and Instrumentation** | | | | | | | |
| 33 | Supply | | | LS | $ 50,000 | 1 | $ 50,000 |
| 34 | Control Systems and Instrumentation | | | LS | $ 30,000 | 1 | $ 30,000 |
| 35 | Control Wiring | | | LS | $ 5,000 | 1 | 5,000 |
| **Rounded Subtotal*** | | | | | | | $ 1,128,000 |

| | | | | |
|---|---|---|---|---|
| **General Contractor Indirect Costs** | | | | |
| Construction Management (Contractor) | | 2.5% | $ 1,128,000 | $ 28,200 |
| Mobilization/Demobilization | LS | $ 22,500 | 1 | $ 22,500 |
| | | Rounded Subtotal* | | $ 51,000 |
| | **Total Construction Costs** | | | $ 1,179,000 |
| | Contingencies | | **35%** | $ 412,650 |
| **TOTAL CONSTRUCTION COSTS WITH CONTINGENCIES*** | | | | **$ 1,592,000** |
| **Other Project Costs** | | | | |
| Engineering/SDC | | | 10.0% | $ 159,200 |
| Permitting | | | 7.0% | $ 111,440 |
| Construction Services/Inspections | | | 10.0% | $ 159,200 |
| | | Rounded Subtotal* | | $ 430,000 |
| **TOTAL ESTIMATED CAPITAL COSTS** | | | | **$ 2,022,000** |
| **RECURRING CAPITAL EXPENSES** | **REPLACEMENT INTERVAL** | | | |
| Pump Motor | 10 | yrs | | $ 5,000 |
| Impeller | 10 | yrs | | $ 5,000 |
| Diffuser Lateral | 10 | yrs | | $ 101,600 |
| Oxygen Diffuser | 5 | yrs | | $ 6,000 |
| **Total Recurring Capital Expenses** | | Rounded Subtotal* | | **$ 118,000** |
| **ANNUAL OPERATION AND MAINTENANCE COSTS** | | | | |
| Equipment Maintenance (Equipment and Mechanical) | | | 3.0% | $ 12,370 |
| Monitoring and Adaptive Management | | | 2.0% | $ 40,440 |
| Oxygen Tank Rental | Month | $ 750 | 12 | $ 9,000 |
| Oxygen Supply (13,700 lbs/day) | lbs | $ 0.07 | 1,370,000 | $ 95,900 |
| Power Costs | kW-hr | $ 0.06 | 80,540 | $ 4,840 |
| **Total Annual O & M Costs*** | | | | **$ 163,000** |

*Rounded up to the nearest $1,000.

HDR | ONE COMPANY | Many Solutions™

**PRELIMINARY COST ESTIMATE**

## U-TUBE ALTERNATIVE D - ONE 6' OUTER DIAMETER (3' OUTER RADIUS) U-TUBE X 115 FT HEIGHT

**ENGINEER'S COST OPINION: PRELIMINARY DESIGN**
**CALIFORNIA BAY DELTA AUTHORITY**
**SAN JOAQUIN RIVER AERATION ENGINEERING FEASIBILITY STUDY**
**DATE: JULY 2, 2004** **CHD: JUL 6, 2004**

**Construction Costs**

| Item | Description | | | Unit | Unit Price | Quantity | Item Price |
|---|---|---|---|---|---|---|---|
| **Division 1 - General Requirements** | | | | | | | |
| | | | | | | | |
| **Division 2 - Site Work** | | | | | | | |
| 1 | Cut/Fill | | | CY | $ 5 | 725 | $ 3,625 |
| 2 | Removable Bollards | | | EA | $ 300 | 6 | $ 1,800 |
| 3 | Fencing | | | LS | $ 6,500 | 1 | $ 6,500 |
| 4 | 9" AB | | | CY | $ 36 | 50 | $ 1,800 |
| 5 | 3" AC | | | SF | $ 5 | 1600 | $ 8,000 |
| **Division 3 - Concrete** | | | | | | | |
| 6 | $O_2$ Tank Slab | | | CY | $ 500 | 18 | $ 9,000 |
| 7 | Building Slab | | | CY | $ 500 | 10 | $ 5,000 |
| 8 | Wet Well | | | LS | $ 6,500 | 1 | $ 6,500 |
| **Division 4 - Masonry** | | | | | | | |
| 9 | Split-block Masonry Building (20' x 20') | | | SF | $ 250 | 400 | $ 100,000 |
| **Division 9 - Finishes** | | | | | | | |
| 10 | Coatings | | | LS | $ 20,000 | 1 | $ 20,000 |
| **Division 11 - Equipment** | | | | | | | |
| 11 | Vertical Turbine Pumps and Appurtenances | | | EA | $ 76,500 | 2 | $ 153,000 |
| 12 | Drill & Prep 6' Diameter U-Tube Shaft | | | FT | $ 871 | 115 | $ 100,165 |
| 13 | Casing Material (Assume Welded Steel, 1") | | | LB | $ 1 | 87,300 | $ 87,300 |
| 14 | Install U-Tube Casing | | | FT | $ 50 | 115 | $ 5,750 |
| 15 | Install Bottom Plug (concrete and mortar) | | | CY | $ 500 | 25 | $ 12,500 |
| 16 | Pump Water from Shaft and Prepare Casing | | | LS | $ 35,000 | 1 | $ 35,000 |
| 17 | Bubble Collector and Appurtenances | | | EA | $ 8,000 | 1 | $ 8,000 |
| 18 | Oxygen Diffusers | | | EA | $ 3,000 | 1 | $ 3,000 |
| 19 | Fish Screen (Barrel) | | | EA | $ 500,000 | 1 | $ 500,000 |
| **Division 13 - Special Construction** | | | | | | | |
| 20 | Pressure Gages/Transmitters | | | EA | $ 1,500 | 2 | $ 3,000 |
| 21 | Flow Meter (12" Mag) | | | EA | $ 13,500 | 1 | $ 13,500 |
| **Division 15 - Mechanical** | | | | | | | |
| 22 | $O_2$ Supply Line Piping and Appurtenances | | | LF | $ 12 | 100 | $ 1,200 |
| 23 | $O_2$ Control Valve | | | EA | $ 3,000 | 2 | $ 6,000 |
| 24 | 20" Pump Control Valve | | | EA | $ 28,000 | 2 | $ 56,000 |
| 25 | Isolation Valves | | | EA | $ 14,000 | 3 | $ 42,000 |
| 26 | 20" Ductile Iron Pipe (Header) | $/Dia-In | 20 | LF | $ 180 | 40 | $ 7,200 |
| 27 | 30" Ductile Iron Pipe (Collector/Disch) | $/Dia-In | 30 | LF | $ 270 | 20 | $ 5,400 |
| 28 | 20" Ductile Iron Pipe (Discharge) | $/Dia-In | 20 | LF | $ 180 | 21 | $ 3,780 |
| 29 | 20" Flexible Piping | $/Dia-In | 20 | LF | $ 180 | 120 | $ 21,600 |
| 30 | Inner Piping System | $/Dia-In | 50 | LF | $ 450 | 60 | $ 27,000 |
| 31 | HDPE Diffuser Pipe (Assume 24" Dia) | $/Dia-In | 20 | LF | $ 15 | 1600 | $ 24,000 |
| 32 | Pressure Regulating Station | | | EA | $ 5,000 | 8 | $ 40,000 |
| 33 | Diffuser Supports | | | EA | $ 150 | 160 | $ 24,000 |
| 34 | Lateral Installation (Within Water Column) | | | LF | $ 94 | 1600 | $ 150,400 |
| **Division 16 - Electrical and Instrumentation** | | | | | | | |
| 35 | Supply | | | LS | $ 50,000 | 1 | $ 50,000 |
| 36 | Control Systems and Instrumentation | | | LS | $ 30,000 | 1 | $ 30,000 |
| 37 | Contol Wiring | | | LS | $ 5,000 | 1 | 5,000 |
| **Rounded Subtotal*** | | | | | | | $ 1,578,000 |

| | | | | | |
|---|---|---|---|---|---|
| **General Contractor Indirect Costs** | | | | | |
| Construction Management (Contractor) | | 2.5% | $ 1,578,000 | $ | 39,450 |
| Mobilization/Demobilization | LS | $ 28,000 | 1 | $ | 28,000 |
| | | Rounded Subtotal* | | $ | 68,000 |
| | **Total Construction Costs** | | | $ | 1,646,000 |
| | Contingencies | | **35%** | $ | 576,100 |
| **TOTAL CONSTRUCTION COSTS WITH CONTINGENCIES*** | | | | **$** | **2,223,000** |
| **Other Project Costs** | | | | | |
| Engineering/SDC | | | 10.0% | $ | 222,300 |
| Permitting | | | 7.0% | $ | 155,610 |
| Construction Services/Inspections | | | 10.0% | $ | 222,300 |
| | | Rounded Subtotal* | | $ | 600,000 |
| **TOTAL ESTIMATED CAPITAL COSTS** | | | | **$** | **2,823,000** |

| **RECURRING CAPITAL EXPENSES** | **REPLACEMENT INTERVAL** | | | |
|---|---|---|---|---|
| Pump Motor | 10 | yrs | $ | 12,000 |
| Impeller | 10 | yrs | $ | 10,000 |
| Diffuser Lateral | 10 | yrs | $ | 198,400 |
| Oxygen Diffuser | 5 | yrs | $ | 9,000 |
| **Total Recurring Capital Expenses** | | Rounded Subtotal* | **$** | **230,000** |

| **ANNUAL OPERATION AND MAINTENANCE COSTS** | | | | | |
|---|---|---|---|---|---|
| Equipment Maintenance (Equipment and Mechanical) | | | 3.0% | $ | 12,060 |
| Monitoring and Adaptive Management | | | 2.0% | $ | 56,460 |
| Oxygen Tank Rental | Month | $ 750 | 12 | $ | 9,000 |
| Oxygen Supply (19,200 lbs/day) | lbs | $ 0.07 | 1,920,000 | $ | 134,400 |
| Power Costs | kW-hr | $ 0.06 | 178,970 | $ | 10,740 |
| **Total Annual O & M Costs*** | | | | **$** | **223,000** |

*Rounded up to the nearest $1,000.

ONE COMPANY *Many Solutions*

**PRELIMINARY COST ESTIMATE**

**SPEECE CONE ALTERNATIVE A - LOW PRESSURE**
**2 SPEECE CONES, TOP RADIUS=0.83', BOTTOM RADIUS=4.5'**

**ENGINEER'S COST OPINION: PRELIMINARY DESIGN**
**CAL-FED Bay Delta Authority**
**SAN JOAQUIN RIVER AERATION ENGINEERING FEASIBILITY STUDY**
**DATE: JULY 2, 2004** **CHD: JUNE 24, 2004**

**Construction Costs**

| Item | Description | | | Unit | Unit Price | Quantity | Item Price |
|---|---|---|---|---|---|---|---|
| **Division 1 - General Requirements** | | | | | | | |
| | | | | | | | |
| **Division 2 - Site Work** | | | | | | | |
| 1 | Removable Bollards | | | EA | $ 300 | 6 | $ 1,800 |
| 2 | Fencing | | | LS | $ 6,500 | 1 | $ 6,500 |
| 3 | 9" AB | | | CY | $ 36 | 20 | $ 720 |
| 4 | 3" AC | | | SF | $ 5 | 300 | $ 1,500 |
| **Division 3 - Concrete** | | | | | | | |
| 5 | $O_2$ Tank Slab | | | CY | $ 500 | 15 | $ 7,500 |
| 6 | Building Slab | | | CY | $ 500 | 10 | $ 5,000 |
| **Division 4 - Masonry** | | | | | | | |
| 7 | Split-block Masonry Building (20' x 20') | | | SF | $ 250 | 400 | $ 100,000 |
| **Division 9 - Finishes** | | | | | | | |
| 8 | Coatings | | | LS | $ 10,000 | 1 | $ 10,000 |
| **Division 11 - Equipment** | | | | | | | |
| 9 | Vertical Turbine Pump and Appurtenances | | | EA | $ 45,900 | 2 | $ 91,800 |
| 10 | Speece Cone -15 ft height, 0.83 ft/4.5 ft radius | | | EA | $ 35,000 | 2 | $ 70,000 |
| 11 | Movable Equipment Platform | | | LS | $ 220,000 | 1 | $ 220,000 |
| 12 | Fish Screen | | | EA | $ 240,000 | 1 | $ 240,000 |
| **Division 15 - Special Construction** | | | | | | | |
| 13 | Pressure Gages/Transmitters | | | EA | $ 1,500 | 4 | $ 6,000 |
| 14 | Flow Meter (12" Mag) | | | EA | $ 13,500 | 2 | $ 27,000 |
| **Division 15 - Mechanical** | | | | | | | |
| 15 | $O_2$ Supply Piping and appertenances | | | LF | $ 12 | 65 | $ 780 |
| 16 | $O_2$ Control Valve | | | EA | $ 2,500 | 2 | $ 5,000 |
| 17 | 12" Ductile Iron Pipe | $/Dia-In | 12 | LF | $ 108 | 60 | $ 6,480 |
| 18 | Vent | $/Dia-In | 2 | LF | $ 6 | 30 | $ 180 |
| 19 | 12" Flexible Connection | $/Dia-In | 12 | LF | $ 108 | 60 | $ 6,480 |
| 20 | Other Miscellaneous Piping | | | LS | $ 4,500 | 1 | $ 4,500 |
| 21 | Throttling Valve | | | EA | $ 3,400 | 2 | $ 6,800 |
| 22 | 12" Pump Control Valve | | | EA | $ 8,000 | 2 | $ 16,000 |
| 23 | HDPE Diffuser Pipe | $/Dia-In | 20 | LF | $ 10 | 800 | $ 8,000 |
| 24 | Diffuser Supports | | | EA | $ 150 | 80 | $ 12,000 |
| 25 | Diffuser in Speece-Cone for oxygen | | | LS | $ 1,000 | 2 | $ 2,000 |
| 26 | Lateral Installation | | | LF | $ 94 | 800 | $ 75,200 |
| **Division 16 - Electrical and Instrumentation** | | | | | | | |
| 27 | Supply | | | LS | $ 50,000 | 1 | $ 50,000 |
| 28 | Control Systems and Instrumentation | | | EA | $ 40,000 | 1 | $ 40,000 |
| 29 | Control Wiring | | | LS | $ 12,000 | 2 | $ 24,000 |
| **Rounded Subtotal*** | | | | | | | $ 1,046,000 |

| | | | | |
|---|---|---|---|---|
| **General Contractor Indirect Costs** | | | | |
| Construction Management (Contractor) | | 2.5% | $ 1,046,000 | $ 26,150 |
| Mobilization | | 2.0% | $ 1,046,000 | $ 20,920 |
| | | Rounded Subtotal* | | $ 47,000 |
| | **Total Construction Costs** | | | $ 1,093,000 |
| | Contingencies | | **35%** | $ 382,550 |
| **TOTAL CONSTRUCTION COSTS WITH CONTINGENCIES*** | | | | **$ 1,476,000** |
| | | | | |
| **Other Project Costs** | | | | |
| Engineering/SDC | | | 10.0% | $ 147,600 |
| Permitting | | | 7.0% | $ 103,320 |
| Construction Services/Inspections | | | 10.0% | $ 147,600 |
| | | Rounded Subtotal* | | $ 399,000 |
| **TOTAL ESTIMATED CAPITAL COSTS** | | | | **$ 1,875,000** |

| | | | | |
|---|---|---|---|---|
| **RECURRING CAPITAL EXPENSES** | REPLACEMENT INTERVAL | | | |
| Pump Motor | 10 | yrs | | $ 10,000 |
| Impeller | 10 | yrs | | $ 10,000 |
| Diffuser Lateral | 10 | yrs | | $ 95,200 |
| Diffusers in Speece (2X) | 5 | yrs | | $ 6,000 |
| **Total Recurring Capital Expenses** | | Rounded Subtotal* | | **$ 122,000** |

| | | | | |
|---|---|---|---|---|
| **ANNUAL OPERATION AND MAINTENANCE** | | | | |
| Pumps | | | 2.5% | $ 2,300 |
| Pipes | | | 1.0% | $ 2,680 |
| Monitoring and Adaptive Management | | | 2.0% | $ 37,500 |
| Oxygen Tank Rental | Month | $ 750.00 | 12 | $ 9,000 |
| Oxygen Supply (13,333 lbs/day) | lbs | $ 0.07 | 1,333,300 | $ 93,340 |
| Power Costs | kW-hr | $ 0.06 | 107,381 | $ 6,450 |
| **Total Annual O & M Costs*** | | | | **$ 152,000** |

*Rounded up to the nearest $1,000.

HDR | ONE COMPANY Many Solutions

**PRELIMINARY COST ESTIMATE**

**SPEECE CONE ALTERNATIVE B - PRESSURIZED**
**2 SPEECE CONES, TOP RADIUS=0.83', BOTTOM RADIUS=4.5'**

**ENGINEER'S COST OPINION: PRELIMINARY DESIGN**
**CAL-FED Bay Delta Authority**
**SAN JOAQUIN RIVER AERATION ENGINEERING FEASIBILITY STUDY**
**DATE: JULY 2, 2004** **CHD: JUNE 24, 2004**

**Construction Costs**

| Item | Description | | | Unit | Unit Price | Quantity | Item Price |
|---|---|---|---|---|---|---|---|
| **Division 1 - General Requirements** | | | | | | | |
| | | | | | | | |
| **Division 2 - Site Work** | | | | | | | |
| 1 | Removable Bollards | | | EA | $ 300 | 6 | $ 1,800 |
| 2 | Fencing | | | LS | $ 6,500 | 1 | $ 6,500 |
| 3 | 9" AB | | | CY | $ 36 | 20 | $ 720 |
| 4 | 3" AC | | | SF | $ 5 | 300 | $ 1,500 |
| **Division 3 - Concrete** | | | | | | | |
| 5 | $O_2$ Tank Slab | | | CY | $ 500 | 15 | $ 7,500 |
| 6 | Building Slab | | | CY | $ 500 | 10 | $ 5,000 |
| **Division 4 - Masonry** | | | | | | | |
| 7 | Split-block Masonry Building (20' x 20') | | | SF | $ 250 | 400 | $ 100,000 |
| **Division 9 - Finishes** | | | | | | | |
| 8 | Coatings | | | LS | $ 10,000 | 1 | $ 10,000 |
| **Division 11 - Equipment** | | | | | | | |
| 9 | Vertical Turbine Pump and Appurtenances | | | EA | $ 105,000 | 2 | $ 210,000 |
| 10 | Speece Cone -15 ft height, 0.83 ft/4.5 ft radius | | | EA | $ 35,000 | 2 | $ 70,000 |
| 11 | Movable Equipment Platform | | | LS | $ 220,000 | 1 | $ 220,000 |
| 12 | Fish Screen | | | EA | $ 240,000 | 1 | $ 240,000 |
| **Division 13 - Special Construction** | | | | | | | |
| 13 | Pressure Gages/Transmitters | | | EA | $ 1,500 | 4 | $ 6,000 |
| 14 | Flow Meter (12" Mag) | | | EA | $ 13,500 | 2 | $ 27,000 |
| **Division 15 - Mechanical** | | | | | | | |
| 15 | $O_2$ Supply Piping and Appurtanances | | | LF | $ 12 | 65 | $ 780 |
| 16 | $O_2$ Control Valve | | | EA | $ 2,500 | 2 | $ 5,000 |
| 17 | 10" Ductile Iron Pipe | $/Dia-In | 10 | LF | $ 30 | 40 | $ 1,200 |
| 18 | Vent | $/Dia-In | 2 | LF | $ 6 | 30 | $ 180 |
| 19 | 12" Ductile Iron Pipe | $/Dia-In | 10 | LF | $ 50 | 20 | $ 1,000 |
| 20 | 12" Flexible Connection | $/Dia-In | 12 | EA | $ 60 | 60 | $ 3,600 |
| 21 | Other Misc Piping | | | LS | $ 4,500 | 1 | $ 4,500 |
| 22 | Throttling Valve | | | EA | $ 3,400 | 2 | $ 6,800 |
| 23 | 12" Pump Control Valve | | | EA | $ 8,000 | 2 | $ 16,000 |
| 24 | HDPE Diffuser Pipe | $/Dia-In | 12 | LF | $ 9 | 800 | $ 7,200 |
| 25 | Diffuser Supports | | | EA | $ 150 | 40 | $ 6,000 |
| 26 | Diffuser in Speece-Cone for oxygen | | | EA | $ 1,000.00 | 2 | $ 2,000 |
| 27 | Lateral Installation | | | LF | $ 94 | 800 | $ 75,200 |
| **Division 16 - Electrical and Instrumentation** | | | | | | | |
| 28 | Supply | | | LS | $ 50,000 | 1 | $ 50,000 |
| 29 | Control Systems and Instrumentation | | | LS | $ 40,000 | 1 | $ 40,000 |
| 30 | Control Wiring | | | LS | $ 12,000 | 1 | 12,000 |
| **Rounded Subtotal*** | | | | | | | $ 1,138,000 |

| | | | | |
|---|---|---|---|---|
| **General Contractor Indirect Costs** | | | | |
| Construction Management (Contractor) | | 2.5% | $ 1,138,000 | $ 28,450 |
| Mobilization/Demobilization | | 2.0% | $ 1,138,000 | $ 22,760 |
| | Rounded Subtotal* | | | $ 52,000 |
| | **Total Construction Costs** | | | $ 1,190,000 |
| | Contingencies | | **35%** | $ 416,500 |
| **TOTAL CONSTRUCTION COSTS WITH CONTINGENCIES*** | | | | **$ 1,607,000** |
| **Other Project Costs** | | | | |
| Engineering/SDC | | | 10.0% | $ 160,700 |
| Permitting | | | 7.0% | $ 112,490 |
| Construction Services/Inspections | | | 10.0% | $ 160,700 |
| | Rounded Subtotal* | | | $ 434,000 |
| **TOTAL ESTIMATED CAPITAL COSTS** | | | | **$ 2,041,000** |

| | | | | |
|---|---|---|---|---|
| **RECURRING CAPITAL EXPENSES** | **REPLACEMENT INTERVAL** | | | |
| Pump Motor (2X) | 10 | yrs | | $ 14,000 |
| Impeller | 10 | yrs | | $ 10,000 |
| Diffuser Lateral | 10 | yrs | | $ 88,400 |
| Diffusers in Speece (2X) | 5 | yrs | | $ 6,000 |
| **Total Recurring Capital Expenses** | | Rounded Subtotal* | | **$ 119,000** |

| | | | | |
|---|---|---|---|---|
| **ANNUAL OPERATION AND MAINTENANCE COSTS** | | | | |
| Pumps | | | 2.5% | $ 5,250 |
| Pipes | | | 1.0% | $ 3,650 |
| Monitoring and Adaptive Management | | | 2.0% | $ 40,820 |
| Oxygen Tank Rental | Month | $ 750 | 12 | $ 9,000 |
| Oxygen Supply (10,737 lbs/day) | lbs | $ 0.07 | 1,073,700 | $ 75,160 |
| Power Costs | kW-hr | $ 0.06 | 429,523 | $ 25,780 |
| **Total O & M Costs** | | | | **$ 160,000** |

*Rounded up to the nearest $1,000.

ONE COMPANY
*Many Solutions*

## PRELIMINARY COST ESTIMATE

**SPEECE CONE ALTERNATIVE C - PRESSURIZED**
**1 SPEECE CONE, TOP RADIUS=1.8', BOTTOM RADIUS=9.4'**

**ENGINEER'S COST OPINION: PRELIMINARY DESIGN**
**CAL-FED Bay Delta Authority**
**SAN JOAQUIN RIVER AERATION ENGINEERING FEASIBILITY STUDY**
**Construction Costs** — **DATE: JULY 2, 2004** — **CHD: JUNE 24, 2004**

| Item | Description | | | Unit | Unit Price | Quantity | Item Price |
|---|---|---|---|---|---|---|---|
| **Division 1 - General Requirements** | | | | | | | |
| | | | | | | | |
| **Division 2 - Site Work** | | | | | | | |
| 1 | Removable Bollards | | | EA | $ 300 | 6 | $ 1,800 |
| 2 | Fencing | | | LS | 6500 | 1 | 6500 |
| 3 | 9" AB | | | CY | $ 36 | 20 | $ 720 |
| 4 | 3" AC | | | SF | $ 5 | 300 | $ 1,500 |
| **Division 3 - Concrete** | | | | | | | |
| 5 | $O_2$ Tank Slab | | | CY | $ 500 | 15 | $ 7,500 |
| 6 | Building Slab | | | CY | $ 500 | 10 | $ 5,000 |
| **Division 4 - Masonry** | | | | | | | |
| 7 | Split-block Masonry Building (20' x 20') | | | SF | $ 250 | 400 | $ 100,000 |
| **Division 9 - Finishes** | | | | | | | |
| 8 | Coatings | | | LS | $ 10,000 | 1 | $ 10,000 |
| **Division 11 - Equipment** | | | | | | | |
| 9 | Vertical Turbine Pump and Appurtenances | | | EA | $ 45,900 | 3 | $ 137,700 |
| 10 | Speece Cone (30 ft height) | | | EA | $ 80,500 | 2 | $ 161,000 |
| 11 | Movable Equipment Platform | | | LS | $ 220,000 | 1 | $ 220,000 |
| 12 | Fish Screen (Barrel) | | | EA | $ 500,000 | 1 | $ 500,000 |
| **Division 13 - Special Construction** | | | | | | | |
| 13 | Pressure Gages/Transmitters | | | EA | $ 1,500 | 4 | $ 6,000 |
| 14 | Flow Meter (12" Mag) | | | EA | $ 13,500 | 2 | $ 27,000 |
| **Division 15 - Mechanical** | | | | | | | |
| 15 | $O_2$ Supply Piping and Appurtanances | | | LF | $ 12 | 65 | $ 780 |
| 16 | $O_2$ Control Valve | | | EA | $ 2,500 | 2 | $ 5,000 |
| 17 | 24" Ductile Iron Pipe (Header) | $/Dia-In | 24 | LF | $ 216 | 60 | $ 12,960 |
| 18 | Vent | $/Dia-In | 2 | LF | $ 6 | 30 | $ 180 |
| 19 | 24" Ductile Iron Pipe (Discharge) | $/Dia-In | 24 | LF | $ 216 | 20 | $ 4,320 |
| 20 | 24" Flexible Connection | $/Dia-In | 24 | EA | $ 216 | 60 | $ 12,960 |
| 21 | Other Misc Piping | | | LS | $ 4,500 | 1 | $ 4,500 |
| 22 | Throttling Valve | | | EA | $ 3,400 | 2 | $ 6,800 |
| 23 | 24" Pump Control Valve | | | EA | $ 30,000 | 2 | $ 60,000 |
| 24 | HDPE Diffuser Pipe | $/Dia-In | 12 | LF | $ 9 | 1600 | $ 14,400 |
| 25 | Diffuser Supports | | | EA | $ 150 | 160 | $ 24,000 |
| 26 | Diffuser in Speece-Cone for oxygen | | | EA | $ 1,000 | 2 | $ 2,000 |
| 27 | Lateral Installation | | | LF | $ 94 | 1600 | $ 150,400 |
| **Division 16 - Electrical and Instrumentation** | | | | | | | |
| 28 | Supply | | | LS | $ 50,000 | 1 | $ 50,000 |
| 29 | Control Systems and Instrumentation | | | LS | $ 40,000 | 1 | $ 40,000 |
| 30 | Control Wiring | | | LS | $ 12,000 | 1 | 12,000 |
| **Rounded Subtotal*** | | | | | | | $ 1,586,000 |

| | | | | |
|---|---|---|---|---|
| **General Contractor Indirect Costs** | | | | |
| Construction Management (Contractor) | 2.5% | $ 1,586,000 | $ | 39,650 |
| Mobilization/Demobilization | 2.0% | $ 1,586,000 | $ | 31,720 |
| | Rounded Subtotal* | | $ | 72,000 |
| | **Total Construction Costs** | | $ | 1,658,000 |
| | Contingencies | **35%** | $ | 580,300 |
| **TOTAL CONSTRUCTION COSTS WITH CONTINGENCIES*** | | | **$** | **2,239,000** |
| **Other Project Costs** | | | | |
| Engineering/SDC | | 10.0% | $ | 223,900 |
| Permitting | | 7.0% | $ | 156,730 |
| Construction Services/Inspections | | 10.0% | $ | 223,900 |
| | Rounded Subtotal* | | $ | 605,000 |
| **TOTAL ESTIMATED CAPITAL COSTS** | | | **$** | **2,844,000** |

| | | | | |
|---|---|---|---|---|
| **RECURRING CAPITAL EXPENSES** | **REPLACEMENT INTERVAL** | | | |
| Pump Motor | 10 | yrs | $ | 18,000 |
| Impeller | 10 | yrs | $ | 10,000 |
| Diffuser Lateral | 10 | yrs | $ | 188,800 |
| Diffusers in Speece (2X) | 5 | yrs | $ | 6,000 |
| **Total Recurring Capital Expenses** | | Rounded Subtotal* | **$** | **223,000** |

| | | | | | |
|---|---|---|---|---|---|
| **ANNUAL OPERATION AND MAINTENANCE COSTS** | | | | | |
| Pumps | | | 2.5% | $ | 3,443 |
| Pipes | | | 1.0% | $ | 8,090 |
| Monitoring and Adaptive Management | | | 2.0% | $ | 56,880 |
| Oxygen Tank Rental | Month | $ 750 | 12 | $ | 9,000 |
| Oxygen Supply (14,444 lbs/day) | lbs | $ 0.07 | 1,444,400 | $ | 101,110 |
| Power Costs | kW-hr | $ 0.06 | 1,234,879 | $ | 74,100 |
| **Total O & M Costs*** | | | | **$** | **253,000** |

*Rounded up to the nearest $1,000.

HDR ONE COMPANY *Many Solutions*℠

**PRELIMINARY COST ESTIMATE**

**BUBBLE PLUME ALTERNATIVE A - AIR**

**ENGINEER'S COST OPINION: PRELIMINARY DESIGN**
**CAL-FED Bay Delta Authority**
**SAN JOAQUIN RIVER AERATION ENGINEERING FEASIBILITY STUDY**
**DATE: JULY 2, 2004** **CHD: JUNE 24, 2004**

**Construction Costs**

| Item | Description | | | Unit | | Unit Price | Quantity | | Item Price |
|---|---|---|---|---|---|---|---|---|---|
| **Division 1 - General Requirements** | | | | | | | | | |
| | | | | | | | | | |
| **Division 2 - Site Work** | | | | | | | | | |
| 1 | Removable Bollards | | | EA | $ | 300 | 6 | $ | 2,000 |
| 2 | Fencing | | | LS | $ | 6,500 | 1 | $ | 6,500 |
| 3 | 9" AB | | | CY | $ | 36 | 45 | $ | 1,620 |
| 4 | 3" AC | | | SF | $ | 5 | 1600 | $ | 8,000 |
| **Division 3 - Concrete** | | | | | | | | | |
| 5 | Building Slab | | | CY | $ | 500 | 10 | $ | 5,000 |
| **Division 4 - Masonry** | | | | | | | | | |
| 6 | Split-block Masonry Building (20' x 20') | | | SF | $ | 250 | 400 | $ | 100,000 |
| **Division 9 - Finishes** | | | | | | | | | |
| 7 | Coatings | | | LS | $ | 10,000 | 1 | $ | 10,000 |
| **Division 11 - Equipment** | | | | | | | | | |
| 8 | Compressor and Appurtenances | | | EA | $ | 26,000 | 1 | $ | 26,000 |
| **Division 15 - Mechanical** | | | | | | | | | |
| 9 | Distribution Line (10" HDPE) | Dia | 10 | LF | $ | 5 | 5500 | $ | 27,500 |
| 10 | Air Bubble Diffuser | | | LF | $ | 12 | 5500 | $ | 66,000 |
| 11 | Diffuser Supports and Anchorage | | | EA | $ | 150 | 550 | $ | 82,500 |
| 12 | Diffuser Installation | | | LF | $ | 94 | 11000 | $ | 1,034,000 |
| 13 | Pressure Regulating Station | | | EA | $ | 5,000 | 27 | $ | 135,000 |
| **Division 16 - Electrical and Instrumentation** | | | | | | | | | |
| 14 | Supply | | | LS | $ | 50,000 | 1 | $ | 50,000 |
| 15 | Control Systems and Instrumentation | | | EA | $ | 35,000 | 1 | $ | 35,000 |
| 16 | Control Wiring | | | LS | | 5,500 | 1 | | 5,500 |
| **Rounded Subtotal*** | | | | | | | | $ | 1,595,000 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **General Contractor Indirect Costs** | | | | | | |
| Construction Management (Contractor) | | 2.5% | $ | 1,595,000 | $ | 39,875 |
| Mobilization | | 2.0% | $ | 1,595,000 | $ | 31,900 |
| | Rounded Subtotal* | | | | $ | 72,000 |
| | **Total Construction Costs** | | | | $ | 1,667,000 |
| | Contingencies | | | **35%** | $ | 583,450 |
| **TOTAL CONSTRUCTION COSTS WITH CONTINGENCIES*** | | | | | **$** | **2,251,000** |
| **Other Project Costs** | | | | | | |
| Engineering/SDC | | | | 10.0% | $ | 225,100 |
| Permitting | | | | 7.0% | $ | 157,570 |
| Construction Services/Inspections | | | | 10.0% | $ | 225,100 |
| | Rounded Subtotal* | | | | **$** | **608,000** |
| **TOTAL ESTIMATED CAPITAL COSTS** | | | | | **$** | **2,859,000** |
| **RECURRING CAPITAL EXPENSES** | **REPLACEMENT INTERVAL** | | | | | |
| Air Bubble Diffuser | 10 | yrs | | | $ | 1,182,500 |
| Compressor Motor | 10 | yrs | | | $ | 5,000 |
| **Total Recurring Capital Expenses** | Rounded Subtotal* | | | | **$** | **1,188,000** |
| **TOTAL ANNUAL OPERATION AND MAINTENANCE COSTS** | | | | | | |
| Equipment and Maintenance (Equipment and Mechanical) | | | | 10.0% | $ | 124,000 |
| Monitoring and Adaptive Management | | | | 3.0% | $ | 86,000 |
| Power Costs | kW-hr | $ | 0.06 | 84,120 | $ | 5,000 |
| **Total Annual O & M Costs*** | | | | | **$** | **215,000** |

*Rounded up to the nearest $1,000.

HDR | ONE COMPANY *Many Solutions*

**PRELIMINARY COST ESTIMATE**

## BUBBLE PLUME ALTERNATIVE B - AIR

**ENGINEER'S COST OPINION: PRELIMINARY DESIGN**
**CAL-FED Bay Delta Authority**
**SAN JOAQUIN RIVER AERATION ENGINEERING FEASIBILITY STUDY**
**DATE: JULY 2, 2004** **CHD: JUNE 24, 2004**

**Construction Costs**

| Item | Description | | | Unit | | Unit Price | Quantity | | Item Price |
|---|---|---|---|---|---|---|---|---|---|
| **Division 1 - General Requirements** | | | | | | | | | |
| **Division 2 - Site Work** | | | | | | | | | |
| 1 | Removable Bollards | | | EA | $ | 300 | 6 | $ | 2,000 |
| 2 | Fencing | | | LS | $ | 6,500 | 1 | $ | 6,500 |
| 3 | 9" AB | | | CY | $ | 36 | 45 | $ | 1,620 |
| 4 | 3" AC | | | SF | $ | 5 | 1600 | $ | 8,000 |
| **Division 3 - Concrete** | | | | | | | | | |
| 5 | Building Slab | | | CY | $ | 500 | 10 | $ | 5,000 |
| **Division 4 - Masonry** | | | | | | | | | |
| 6 | Split-block Masonry Building (20' x 20') | | | SF | $ | 250 | 400 | $ | 100,000 |
| **Division 9 - Finishes** | | | | | | | | | |
| 7 | Coatings | | | LS | $ | 10,000 | 1 | $ | 10,000 |
| **Division 11 - Equipment** | | | | | | | | | |
| 8 | Compressor and Appurtenances | | | EA | $ | 52,000 | 1 | $ | 52,000 |
| **Division 15 - Mechanical** | | | | | | | | | |
| 9 | Distribution Line | Dia | 12 | LS | $ | 6 | 3000 | $ | 18,000 |
| 10 | Air Bubble Diffuser | | | LF | $ | 12 | 3000 | $ | 36,000 |
| 11 | Diffuser Supports and Anchorage | | | EA | $ | 150 | 300 | $ | 45,000 |
| 12 | Diffuser Installation | | | LF | $ | 94 | 6000 | $ | 564,000 |
| 13 | Pressure Regulating Station | | | EA | $ | 5,000 | 15 | $ | 75,000 |
| **Division 16 - Electrical and Instrumentation** | | | | | | | | | |
| 14 | Supply | | | LS | $ | 50,000 | 1 | $ | 50,000 |
| 15 | Control Systems and Instrumentation | | | EA | $ | 35,000 | 1 | $ | 35,000 |
| 16 | Control Wiring | | | LS | | 5,500 | 1 | | 5,500 |
| **Rounded Subtotal*** | | | | | | | | $ | 1,014,000 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **General Contractor Indirect Costs** | | | | | | |
| Construction Management (Contractor) | | 2.5% | $ | 1,014,000 | $ | 25,350 |
| Mobilization | | 2.0% | $ | 1,014,000 | $ | 20,280 |
| | Rounded Subtotal* | | | | $ | 46,000 |
| | **Total Construction Costs** | | | | $ | 1,060,000 |
| | Contingencies | | | **35%** | $ | 371,000 |
| **TOTAL CONSTRUCTION COSTS WITH CONTINGENCIES** | | | | | **$** | **1,431,000** |

**Other Project Costs**

| | | | | |
|---|---|---|---|---|
| Engineering/SDC | | 10.0% | $ | 143,100 |
| Permitting | | 7.0% | $ | 100,170 |
| Construction Services/Inspections | | 10.0% | $ | 143,100 |
| | Rounded Subtotal* | | **$** | **387,000** |
| **TOTAL ESTIMATED CAPITAL COSTS** | | | **$** | **1,818,000** |

| | | | | | |
|---|---|---|---|---|---|
| **RECURRING CAPITAL EXPENSES** | **REPLACEMENT INTERVAL** | | | | |
| Air Bubble Diffuser | 10 | yrs | | $ | 645,000 |
| Compressor Motor | 10 | yrs | | $ | 10,000 |
| **Total Recurring Capital Expenses** | | | **Subtotal** | **$** | **655,000** |

| | | | | | | |
|---|---|---|---|---|---|---|
| **TOTAL ANNUAL OPERATION AND MAINTENANCE COSTS** | | | | | | |
| Equipment and Maintenance (Equipment and Mechanical) | | | | 10.0% | $ | 71,500 |
| Monitoring and Adaptive Management | | | | 3.0% | $ | 54,540 |
| Power Costs | kW-hr | $ | 0.06 | 155,710 | $ | 9,350 |
| **Total Annual O & M Costs*** | | | | | **$** | **136,000** |

*Rounded up to the nearest $1,000.

HDR | ONE COMPANY *Many Solutions*℠

**PRELIMINARY COST ESTIMATE**

**BUBBLE PLUME ALTERNATIVE C - OXYGEN**

**ENGINEER'S COST OPINION: PRELIMINARY DESIGN**
**CAL-FED Bay Delta Authority**
**SAN JOAQUIN RIVER AERATION ENGINEERING FEASIBILITY STUDY**
**DATE: JULY 2, 2004** **CHD: JUNE 24, 2004**

**Construction Costs**

| Item | Description | | | Unit | Unit Price | Quantity | Item Price |
|---|---|---|---|---|---|---|---|
| **Division 1 - General Requirements** | | | | | | | |
| | | | | | | | |
| **Division 2 - Site Work** | | | | | | | |
| 1 | Removable Bollards | | | EA | $ 300 | 6 | $ 1,800 |
| 2 | Fencing | | | LS | $ 6,500 | 1 | $ 6,500 |
| 3 | 9" AB | | | CY | $ 36 | 16 | $ 576 |
| 4 | 3" AC | | | SF | $ 5 | 400 | $ 2,000 |
| **Division 3 - Concrete** | | | | | | | |
| 5 | $O_2$ Tank Slab | | | CY | $ 500 | 15 | $ 7,500 |
| **Division 9 - Finishes** | | | | | | | |
| 6 | Coatings | | | LS | $ 4,000 | 1 | $ 4,000 |
| **Division 15 - Mechanical** | | | | | | | |
| 7 | Distribution Line | Dia | 3 | LF | $ 2 | 1900 | $ 2,850 |
| 8 | $O_2$ Supply Piping and Appurtenances | | | LF | $ 12 | 30 | $ 360 |
| 9 | $O_2$ Control Valve | | | EA | $ 2,500 | 1 | $ 2,500 |
| 10 | Pressure Regulating Station | | | EA | $ 5,000 | 10 | $ 47,500 |
| 11 | Air Bubble Diffuser | | | LF | $ 12 | 1900 | $ 22,800 |
| 12 | Diffuser Supports and Anchorage | | | EA | $ 150 | 190 | $ 28,500 |
| 13 | Diffuser Installation | | | LF | $ 94 | 3800 | $ 357,200 |
| **Division 16 - Electrical and Instrumentation** | | | | | | | |
| 14 | Supply | | | LS | $ 25,000 | 1 | $ 25,000 |
| 15 | Control Systems and Instrumentation | | | EA | $ 15,000 | 1 | $ 15,000 |
| 16 | Control Wiring | | | LS | 3,500 | 1 | $ 3,500.00 |
| **Rounded Subtotal*** | | | | | | | $ 528,000 |

| | | | | |
|---|---|---|---|---|
| **General Contractor Indirect Costs** | | | | |
| Construction Management (Contractor) | | 2.5% | $ 528,000 | $ 13,200 |
| Mobilization | | 2.0% | $ 528,000 | $ 10,560 |
| | Rounded Subtotal* | | | $ 24,000 |
| | **Total Construction Costs** | | | $ 552,000 |
| | Contingencies | **35%** | | $ 193,200 |
| **TOTAL CONSTRUCTION COSTS WITH CONTINGENCIES*** | | | | **$ 746,000** |
| **Other Project Costs** | | | | |
| Engineering/SDC | | 10.0% | | $ 74,600 |
| Permitting | | 7.0% | | $ 52,220 |
| Construction Services/Inspections | | 10.0% | | $ 74,600 |
| | Rounded Subtotal* | | | **$ 202,000** |
| **TOTAL ESTIMATED PROJECT COSTS** | | | | **$ 948,000** |

| **RECURRING CAPITAL EXPENSES** | **REPLACEMENT INTERVAL** | | |
|---|---|---|---|
| Air Bubble Diffuser | 10 | yrs | **$ 408,500** |
| **Total Recurring Capital Expenses*** | | | **$ 409,000** |

| **ANNUAL OPERATION AND MAINTENANCE COSTS** | | | | |
|---|---|---|---|---|
| Equipment and Maintenance (Equipment and Mechanical) | | | 10.0% | $ 94,800 |
| Monitoring and Adaptive Management | | | 3.0% | $ 28,440 |
| Oxygen Tank Rental | Month | $ 750.00 | 12 | $ 9,000 |
| Oxygen Supply | lbs | $ 0.07 | 1,219,500 | $ 85,365 |
| **Total Annual O & M Costs*** | | | | **$ 218,000** |

*Rounded up to the nearest $1,000.

HDR | ONE COMPANY *Many Solutions*

# BUBBLE PLUME ALTERNATIVE D - OXYGEN

## PRELIMINARY COST ESTIMATE

**ENGINEER'S COST OPINION: PRELIMINARY DESIGN**
**CAL-FED Bay Delta Authority**
**SAN JOAQUIN RIVER AERATION ENGINEERING FEASIBILITY STUDY**
**DATE: MAY 17, 2004** **CHD: JUNE 1, 2004**

**Construction Costs**

| Item | Description | | | Unit | | Unit Price | Quantity | | Item Price |
|---|---|---|---|---|---|---|---|---|---|
| **Division 1 - General Requirements** | | | | | | | | | |
| | | | | | | | | | |
| **Division 2 - Site Work** | | | | | | | | | |
| 1 | Removable Bollards | | | EA | $ | 300 | 6 | $ | 1,800 |
| 2 | Fencing | | | LS | $ | 6,500 | 1 | $ | 6,500 |
| 3 | 9" AB | | | CY | $ | 36 | 16 | $ | 576 |
| 4 | 3" AC | | | SF | $ | 5 | 400 | $ | 2,000 |
| **Division 3 - Concrete** | | | | | | | | | |
| 5 | $O_2$ Tank Slab | | | CY | $ | 500 | 15 | $ | 7,500 |
| **Division 9 - Finishes** | | | | | | | | | |
| 6 | Coatings | | | LS | $ | 4,000 | 1 | $ | 4,000 |
| **Division 15 - Mechanical** | | | | | | | | | |
| 7 | Distribution Line | Dia | 4 | LF | $ | 2 | 800 | $ | 1,600 |
| 8 | $O_2$ Supply Piping and Appurtenances | | | LF | $ | 12 | 30 | $ | 360 |
| 9 | $O_2$ Control Valve | | | EA | $ | 2,500 | 1 | $ | 2,500 |
| 10 | Pressure Regulating Station | | | EA | $ | 5,000 | 4 | $ | 20,000 |
| 11 | Air Bubble Diffuser | | | LF | $ | 12 | 800 | $ | 9,600 |
| 12 | Diffuser Supports and Anchorage | | | EA | $ | 100 | 80 | $ | 8,000 |
| 13 | Diffuser Installation | | | LF | $ | 94 | 1600 | $ | 150,400 |
| **Division 16 - Electrical and Instrumentation** | | | | | | | | | |
| 14 | Supply | | | LS | $ | 25,000 | 1 | $ | 25,000 |
| 15 | Control Systems and Instrumentation | | | EA | $ | 15,000 | 1 | $ | 15,000 |
| 16 | Control Wiring | | | LS | | 3,500 | 1 | | 3,500 |
| **Rounded Subtotal*** | | | | | | | | $ | 259,000 |

| | | | | | |
|---|---|---|---|---|---|
| **General Contractor Indirect Costs** | | | | | |
| Construction Management (Contractor) | 2.5% | $ | 259,000 | $ | 6,475 |
| Mobilization | 2.0% | $ | 259,000 | $ | 5,180 |
| | Rounded Subtotal* | | | $ | 12,000 |
| | **Total Construction Costs** | | | $ | 271,000 |
| | Contingencies | | **35%** | $ | 94,850 |
| **TOTAL CONSTRUCTION COSTS WITH CONTINGENCIES*** | | | | **$** | **366,000** |
| **Other Project Costs** | | | | | |
| Engineering/SDC | | | 10.0% | $ | 36,600 |
| Permitting | | | 7.0% | $ | 25,620 |
| Construction Services/Inspections | | | 10.0% | $ | 36,600 |
| | Rounded Subtotal* | | | **$** | **99,000** |
| **TOTAL ESTIMATED PROJECT COSTS** | | | | **$** | **465,000** |

| | | | | | |
|---|---|---|---|---|---|
| **RECURRING CAPITAL EXPENSES** | **REPLACEMENT INTERVAL** | | | | |
| Air Bubble Diffuser | 10 | yrs | | **$** | **168,000** |
| **Total Recurring Capital Expenses** | | | | **$** | **168,000** |

| | | | | | | |
|---|---|---|---|---|---|---|
| **ANNUAL OPERATION AND MAINTENANCE COSTS** | | | | | | |
| Equipment and Maintenance (Equipment and Mechanical) | | | | 10.0% | $ | 46,500 |
| Monitoring and Adaptive Management | | | | 3.0% | $ | 13,950 |
| Oxygen Tank Rental | Month | $ | 750.00 | 12 | $ | 9,000 |
| Oxygen Supply | lbs | $ | 0.07 | 1,538,500 | $ | 107,695 |
| **Total Annual O & M Costs*** | | | | | **$** | **178,000** |

*Rounded up to the nearest $1,000.