Development of an Efficient Aeration System for Aquaculture

by

R. Farmer

and

R.E.A. Arndt

Prepared for

MINNESOTA DEPARTMENT OF AGRICULTURE
St. Paul, Minnesota

June 1995

Minneapolis, Minnesota
Development of an Efficient Aeration System for Aquaculture

by

R. Farmer

and

R.E.A. Arndt

Prepared for

MINNESOTA DEPARTMENT OF AGRICULTURE
St. Paul, Minnesota

June 1995
The University of Minnesota is committed to the policy that all persons shall have equal access to its programs, facilities, and employment without regard to race religion, color, sex, national origin, handicap, age, or veteran status.
ABSTRACT

A new aeration concept developed at the St. Anthony Falls Hydraulic Laboratory can significantly reduce the operating costs for aeration in aquaculture applications. This concept has been thoroughly evaluated in laboratory studies over a period of several years. This research indicated that energy savings of 30 percent or more are possible. This report describes the application of this technology to the development of an aeration system for use in deep water fish farming. Performance measurements were made using procedures established by the American Society of Civil Engineers which is the standard of the industry.

This project was a joint venture between the Saint Anthony Falls Hydraulic Laboratory (SAFHL) and Minnesota Aquafarms, Inc. (MAF). SAFHL was the lead institution in the program. The project was carried out in four phases: 1) Design and laboratory evaluation of a configuration specifically tailored for use in the fish pens of Minnesota Aquafarms, 2) Construction of a prototype system, 3) Operation and evaluation of the prototype system and comparing its performance and energy efficiency against that of the existing aeration system, and 4) Data analysis and final report.

The results of the field studies provided valuable data that will be useful for the design and implementation of improved aeration systems for a broad range of aquaculture applications. Significant information concerning the differences in the operational characteristics of aeration devices with circular and rectangular planform has been obtained. This information will be useful in developing improved versions of the system.
ACKNOWLEDGMENTS

This was a cooperative effort between St. Anthony Falls Hydraulic Laboratory and Minnesota Aquafarms, Inc. Mr. Dwight Wilcox provided invaluable assistance in the planning and execution of the field study. Mr. Richard Noble and Jon Hilde helped with the coordination of the field study. We also acknowledge the efforts of all the other Minnesota Aquafarm employees who extended a hand in carrying out the field study.

A special word of thanks goes to Mr. Gene Zentz of Intertribal Business Network without whose financial support the field study could not have been completed as planned.

Dr. Christopher Ellis of SAFHL provided assistance in the planning and execution of the program. He also provided significant help in the development of instrumentation and the collection of field data. Mr. Benjamin Erickson also assisted in the field measurement program.

This study builds on the work of Dr. V. Ramanathan who developed the original concept as part of his Ph.D. dissertation. He gave freely of his time in helping in the development of a practical aerator based on his previous studies.

This study was carried out under contract with the Minnesota Department of Agriculture.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Abstract</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acknowledgments</td>
<td>ii</td>
</tr>
<tr>
<td>List of figures &amp; tables</td>
<td>v</td>
</tr>
<tr>
<td>Nomenclature</td>
<td>vi</td>
</tr>
</tbody>
</table>

I. Background Information
   1.1 Technology Review  1
   1.2 Objectives and Scope of This Study  1
   1.3 Theoretical Considerations  4
   1.4 Measurement Principles  6

II. Design Issues For SAF Diffuser of Rectangular Planform
   2.1 Description of Current MAF Aerator  8
   2.2 Key Design Parameters for the SAF Diffuser
       2.2.1 Orifice Diameter & Hole Pattern  10
       2.2.2 Length  10
       2.2.3 Number of Diffusers  10
       2.2.4 Air Flowrate  12
       2.2.5 Number of Orifices  12

III. Construction of Diffusers and Aerator Units
   3.1 Materials Used  13
   3.2 Plenum  13
   3.3 Orifices  13
   3.4 Tube Walls  13
   3.5 Alternative Materials Used in Lab Prototype  17
   3.6 Alternative Construction Used in Lab Prototype  17

IV. Laboratory Testing
   4.1 Equipment & Chemicals  18
   4.2 Setup
       4.2.1 DO & Temperature Measurements  18
       4.2.2 Regulation of Air Flowrate  18
       4.2.3 Measurement Procedure  18
       4.2.4 Recording & Analyzing Data  20
   4.3 Parameters Varied in Lab Experiments
       4.3.1 Tube Width and Mouth Width Ratio  20
       4.3.2 Tube Height  21
       4.3.3 Rows of Orifices  21
   4.4 Results of Laboratory Studies  21
   4.5 Discussion  21
V. Field Study

5.1 Aerator Unit Design Parameters

5.2 Field Aerator Setup
   5.2.1 Equipment & Chemicals
   5.2.2 SAF Aerator Platform
   5.2.3 Test Tank
   5.2.3 Placement of SAF & MAF Aerators

5.3 Measurement Procedures
   5.3.1 Effective Tank Volume
   5.3.2 Air Flowrate
   5.3.3 Pressure Drop Across Diffuser Orifices
   5.3.4 DO Concentration
   5.3.5 Temperature
   5.3.6 BOD
   5.3.7 Photosynthesis

5.4 Initial Problems Encountered

5.5 Modifications to SAF Aerator Design

5.6 Data Analysis
   5.6.1 Estimating $K_{L_A}$
   5.6.2 Calculating SOTR
   5.6.3 Calculating SAE
   5.6.4 Field Tests Performed

5.7 Results of Field Studies
   5.7.1 Air Flowrates & Operating Backpressures
   5.7.2 Depth Profiles
   5.7.3 Effective Tank Volume Mixing
   5.7.4 BOD
   5.7.5 $K_{L_A}$ & SAE
   5.7.6 Initial Tests Compared
   5.7.7 Final Tests Compared

5.8 Discussion of Field Study
   5.8.1 Operating Backpressure
   5.8.2 Design Layout
   5.8.3 Effective Mixing
   5.8.4 Oxygen Transfer Rate & Aeration Efficiency
   5.8.5 Plugging

VI. Conclusions

References

Appendix A Equipment and Chemicals
Appendix B Data From Lab Studies
Appendix C Data From Field Studies
LIST OF FIGURES AND TABLES

FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>SAF Diffuser: both circular and rectangular planforms</td>
<td>2</td>
</tr>
<tr>
<td>Figure 2</td>
<td>Bubble formation</td>
<td>5</td>
</tr>
<tr>
<td>Figure 3</td>
<td>MAF aerator with 48 slitted hoses tapping into air supply</td>
<td>9</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Orifice staggered row pattern for perforated brass sheets</td>
<td>11</td>
</tr>
<tr>
<td>Figure 5</td>
<td>Construction of plenum with orifices</td>
<td>14</td>
</tr>
<tr>
<td>Figure 6</td>
<td>Construction of the tube walls</td>
<td>15</td>
</tr>
<tr>
<td>Figure 7</td>
<td>Construction of aerator base and end plugs</td>
<td>16</td>
</tr>
<tr>
<td>Figure 8</td>
<td>Schematic of laboratory experimental tank</td>
<td>19</td>
</tr>
<tr>
<td>Figure 9</td>
<td>K_{LA} values for various rectangular diffuser dimensions</td>
<td>22</td>
</tr>
<tr>
<td>Figure 10</td>
<td>Vortex mixing in diffuser tube</td>
<td>22</td>
</tr>
<tr>
<td>Figure 11</td>
<td>Planview of SAF aerator platform</td>
<td>25</td>
</tr>
<tr>
<td>Figure 12</td>
<td>Tarp bag tank enclosure</td>
<td>27</td>
</tr>
<tr>
<td>Figure 13</td>
<td>Planview of dock setup</td>
<td>27</td>
</tr>
<tr>
<td>Figure 14</td>
<td>Modifications to SAF aerator units</td>
<td>31</td>
</tr>
<tr>
<td>Figure 15</td>
<td>Effective tank volumes for each field test</td>
<td>35</td>
</tr>
<tr>
<td>Figure 16</td>
<td>Bubble area distribution for MAF &amp; SAF aerators</td>
<td>37</td>
</tr>
</tbody>
</table>

TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1</td>
<td>Summary of field tests performed</td>
<td>33</td>
</tr>
<tr>
<td>Table 2</td>
<td>Tank mixing observations</td>
<td>36</td>
</tr>
<tr>
<td>Table 3</td>
<td>Field data summary</td>
<td>39</td>
</tr>
<tr>
<td>Table B1</td>
<td>Results of lab tests on the rectangular prototype diffuser</td>
<td>50</td>
</tr>
<tr>
<td>Table C1</td>
<td>Air flowrates for field studies</td>
<td>51</td>
</tr>
<tr>
<td>Table C2</td>
<td>Summary of pressure drops across orifices for SAF diffusers</td>
<td>51</td>
</tr>
<tr>
<td>Table C3</td>
<td>DO depth profile during field test A</td>
<td>52</td>
</tr>
<tr>
<td>Table C4</td>
<td>DO &amp; temperature depth profiles during field test B</td>
<td>52</td>
</tr>
<tr>
<td>Table C5</td>
<td>DO depth profiles during field test D</td>
<td>52</td>
</tr>
<tr>
<td>Table C6</td>
<td>DO depth profiles during field test E</td>
<td>53</td>
</tr>
<tr>
<td>Table C7</td>
<td>Effective tank volumes from fluorescein tests</td>
<td>53</td>
</tr>
<tr>
<td>Table C8</td>
<td>BOD test results</td>
<td>53</td>
</tr>
<tr>
<td>Table C9</td>
<td>Data summary of oxygen transfer rates &amp; aeration efficiencies</td>
<td>54</td>
</tr>
</tbody>
</table>
NOMENCLATURE

Aeration unit A single 8 ft length of the final SAF aeration device. In initial studies it comprised of six diffusers.

Aerator In the context of this report "aerator" will refer to the 20' x 8' aeration platform tested at the MAF fish farm.

α the void fraction (ratio of the volume of air in a given volume of water).

Aop cross-sectional area of the tube.

Ap cross-sectional area of the inlet tube (or mouth).

BOD biological oxygen demand.

C effective average DO concentration in the liquid phase at any time t.

cfm cubic feet per minute.

C0 dissolved oxygen concentration at t = 0.

Cs dissolved oxygen concentration at saturation.

Css dissolved oxygen concentration at saturation at standard atmospheric pressure and 20° C.

C1 a constant.

Db bubble diameter at the time of detachment from the orifice.

Do orifice diameter.

Diffuser In the context of this report "diffuser" will refer to a single SAF aeration unit used in the design of the aeration platform.

DO dissolved oxygen.

Dop inlet tube (or mouth) width for rectangular planforms or inlet tube (or mouth) diameter for circular planforms.

Dp tube width for rectangular planforms or tube diameter for circular planforms.

Dv distance from the mouth edge to the tube wall, (i.e. the inside width of the top of the plenum); \( D_v = (D_p - D_{op})/2 \).
$F_{Ra}$ air flow Froude number $= (J_a/(Le g)^{1/2})$.

$F_{RW}$ water flow Froude number $= V_w/(Le g)^{1/2})$.

g gravitational acceleration.

$J_a$ superficial air velocity $= (Q_a/A_p)$.

$J_w$ superficial water velocity $= (Q_w/A_p)$.

$k$ ratio of specific heats for air $= 1.4$

$K$ a constant $= (k-1)/k = 0.2857$

$K_{LA}$ mass transfer coefficient.

$K_{La}$ volumetric mass transfer coefficient.

$K_{LA20}$ volumetric mass transfer coefficient at 20° C.

$L_1$ inlet tube (or mouth) height above air inlet.

$L_2$ vertical tube height.

$L_3$ horizontal tube length.

$L_e$ effective tube height $= (L_2 + (L_1(A_{op}/A_p))$.

MAF Minnesota Aquafarms.

effective tank volume the percentage of the test tank volume being effectively mixed by an aerator.

$P_1$ absolute pressure before air compression.

$P_2$ absolute pressure after air compression.

$Q_a$ air flowrate corresponding to the pressure at the tube center.

$Q_{std}$ air flowrate at standard atmosphere.

$Q_w$ induced water flowrate.

$R$ gas constant, 287 Nm/kg·Kelvin.

$\rho$ density of a liquid.

$\sigma$ surface tension.

SAE Standard aeration efficiency—SOTR per unit total power input.
SAF diffuser  The novel aeration device developed and studied at SAFHL.
SAFHL     St. Anthony Falls Hydraulic Laboratory, University of Minnesota.
SAF         St. Anthony Falls, used in naming the novel diffuser developed at that same site.
SAF₅       Original field test design with 5 SAF aerator units—each with 6 diffusers.
SAF₁₀      Original field test design with 10 SAF aerator units—each with 6 diffusers.
SAFₘ       Final field test design with 10 modified SAF aerator units—each with 3 compartmentalized diffusers tested with only one compressor running.
SAFₘ₂      Final field test design with 10 modified SAF aerator units—each with 3 compartmentalized diffusers tested with 2 compressors running in parallel.
scfm       standard cubic feet per minute (cfm at 70°F & 14.7 psig).
SOTR       Standard Oxygen transfer rate—the hypothetical oxygen transfer rate (mass of oxygen per unit time dissolved in a volume of water) when the dissolved oxygen concentration is zero at all points in the water volume when the water temperature is 20°C and the barometric pressure is 1 atm; SOTR = (K_LA₂₀)(Cₜₐₜ).
t         time.
T₁         absolute temperature before air compression in degrees Kelvin.
Vₐ         mean air velocity in the tube = (Jₐ/ω).
V₀         water velocity in the tube inlet upstream of the orifices (orifice water velocity).
Vₜ         mean water velocity in the tube = (Jₜ/(1-ω)).
w         mass flowrate of air (kg/sec).

Note: Both English and metric units are used in this report and are stated where necessary. English units were used because they are the standard of the industry. Metric units were used for scientific experiments.
I. BACKGROUND INFORMATION

1.1 TECHNOLOGY REVIEW

The proposed research pertains to a new diffused aeration device. Diffused aeration devices are usually classified as either fine or coarse bubble diffusers based on the size of the bubbles produced by the diffuser. Coarse bubble diffusers normally produce bubbles in the diameter range of 6-10 mm in clean water whereas the fine bubble diffuses produce bubbles in the diameter range of 2-5 mm in clean water. In most of these devices the main parameter that governs the bubble size is the diameter of the orifice through which the air is injected, a smaller orifice being associated with a smaller bubble.

Fine bubble diffusers are usually made of some porous material and are available in the form of plates, domes, discs and tubes. Coarse bubble diffusers use larger orifices than the fine bubble type. These are available in different types such as fixed orifice (perforated piping, sprayers, slotted tube), valved orifice, static tubes, perforated hose, jet aerator, aspirator and U-tube.

The aeration efficiency (mass of oxygen transferred per unit power input) of a diffused aeration device depends on the bubble size, the bubble rise velocity, the mixing affected by the induced flow and the energy required to compress the air to form bubbles. Current knowledge indicates that the optimum bubble size for an air-water system is on the order of 2 mm (Barnhardt, 1969). Production of bubbles in this size range is usually achieved by using fine bubble diffusers which are made from a porous material having holes of approximately 40 microns in diameter. Because of the very small pore sizes involved, these devices are often subject to severe clogging and consequent deterioration of mass transfer efficiency and escalation of power requirements. One solution to this problem would be to produce the bubbles using larger orifices and to try to optimize the performance of the device by judiciously combining the effects of the other parameters affecting aeration efficiency. With this objective in mind, we have developed a novel aeration device named the "SAF Diffuser" that is expected to be energy conserving with favorable operational characteristics such as being less prone to clogging and having self cleaning features.

1.2 OBJECTIVES AND SCOPE OF THIS STUDY

As already mentioned, the aeration efficiency of an aeration device depends on the bubble size, the bubble rise velocity, the mixing affected by the induced flow and the energy input required to compress the air to produce the bubbles. In order to obtain high transfer efficiencies, it is essential to optimize the combined effect of these parameters. In the SAF Diffused design, this is achieved by controlling the geometric configuration of the device.
D_p = tube width/diameter
D_op = mouth (or inlet tube) width/diameter
D_v = plenum's top side width to tube wall
L_1 = mouth (or inlet tube) height above air inlet
L_2 = vertical tube height
L_3 = horizontal tube length

a. Sectional elevation for both circular and rectangular planforms

b. circular section plan-view

c. rectangular section plan-view

Figure 1. SAF Diffuser: both circular and rectangular planforms
The design of the SAF Diffuser is based on the "air lift" principle. The diffuser is essentially a vertical composite draft tube. The term "composite draft tube" is used to denote a tube whose cross sectional area varies along its length in a prescribed manner. Figure 1 (on the previous page) shows the cross section of the device in its simplest form. The device, as shown, consists of an air injection tube juxtaposed between an inlet and an outlet tube. A buoyancy induced water flow field is created inside the tube by injecting air through orifices located on the periphery of the air injection tube. The drag exerted by the induced flow field on the bubbles being formed at the peripheral orifices causes the bubbles to detach from the orifice when reaching a size that is considerably smaller than a size which they would have otherwise attained in a stagnant water body. For a given air flowrate and orifice arrangement, the induced velocity and hence the size of the bubbles produced by the device depends on the geometric configurations of the inlet and the outlet tubes and the air injection tube. Providing a larger diameter outlet tube as compared to the air injection tube results in lower water velocities in the outlet tube and in turn, decreased bubble rise velocity. The input energy required to compress the air to form the bubbles depends on the size and the number of the peripheral orifices as the depth of placement of the air injection tubes from the water surface. Increasing the length of the inlet tube decreases the input energy requirement. However, there would be an upper limit on the maximum length of the inlet tube dictated by the frictional losses in the tube, the mixing requirements and the decrease in the mass transfer coefficient which occurs when the inlet tube length is increased. The dependence of the bubble size, the bubble rise velocities, the mixing and the energy input on the geometric configuration of the inlet and the outlet tubes, the air injection tube and the size and the number of the peripheral orifices provides a unique way of controlling the aeration efficiency. The geometric proportions of the device and the size and the number of the peripheral orifices can be varied to achieve optimal operation in a variety of applications. The configuration lends itself to mass production and we envisage that by using a modular concept, modules can be combined in different configurations that can be tailored to a wide range of applications and design criteria.

Several geometric configurations of the device are possible. For example, the device can be of circular planform or of rectangular planform. The size of the orifices can be varied from few microns to about 0.5 to 1 mm or even higher values depending upon the water quality and the site specific requirements and they can also be non-circular. These orifices can be arranged along the periphery of the air injection tubes or along the circumference of tubes placed concentrically within the air injection tubes. Since the peripheral orifices are arranged in the vertical plane, it would be possible to accommodate more orifices for a given plan area of the diffuser than would be possible with conventional designs with holes arranged in a horizontal plane. This would result in much reduced energy losses and increase range of application of this device.

Laboratory studies conducted on the SAF diffuser with a circular planform have established its superiority over conventional diffusers with respect to aeration efficiency. This study focused on developing a practical configuration for use in fish farming. The scope of the study encompassed both an in-depth laboratory and field study of a cost effective configuration of the SAF diffuser with a rectangular planform. The laboratory studies were aimed at developing an optimized design of the SAF diffuser with a rectangular planform. The optimized design was then field tested to assess the performance under actual field conditions. The laboratory studies were undertaken at the St. Anthony Falls Hydraulic Laboratory. The field studies were carried at Minnesota Aquafarms, Chisholm, Minnesota. The field studies were carried out in two steps. A preliminary evaluation of the diffuser indicated that some modifications were necessary to account for the difficulty in keeping the device perfectly level. After modifications, an extensive series
of tests were carried out in order to compare the performance with the existing system at Minnesota Aquafarms.

1.3 THEORETICAL CONSIDERATIONS

The important principle of the SAF diffuser is to use a buoyantly induced flow to produce sufficiently small bubbles without resorting to the use of very small holes as illustrated in figure 2. Porous stone diffusers require very small holes to create suitable sized bubbles because the primary mechanism for bubble formation depends on buoyancy to overcome surface tension at the moment of detachment from a hole in a horizontal surface. The very small pores in a porous stone diffuser are subject to clogging and require a very large amount of power to force the air thorough the small holes.

The ratio between bubble size, $d_b$, and hole size, $d_o$, is given by the approximate equation:

$$\frac{d_b}{d_o} = 1.8 \left[ \frac{\sigma}{\rho g d_o^2} \right]^{\frac{1}{3}}$$

where $\rho$ is density of the liquid and $\sigma$ is surface tension. Laboratory experiments confirm Equation 1 for the case of bubbles formed over isolated holes at low flowrate. However this equation actually under-predicts the bubble size in porous stone diffusers. As an example, $d_b$ is predicted to be 1.2 mm when $d_o = 40 \mu m$ in clean water. Measured values for a porous stone diffuser are higher, approximately 3 mm in diameter. The important point is that even with very small pore sizes the resulting bubbles are relatively large.

On the other hand, Silberman (1957) has shown that under certain conditions, bubble size is independent of orifice diameter and surface tension. This occurs when air is injected into a cross flow of velocity $V_o$:

$$\frac{d_b}{d_o} = 2.1 \left[ \frac{V_A}{V_o} \right]^{0.5}$$

where $V_A$ is the velocity of air leaving the orifice. Equation 2 is valid in the limit of high bubble Froude and Weber numbers, $V_o/(gd_b)^{1/2}$ and $\rho V_o^2 d_b/\sigma$ respectively. Silberman found excellent agreement with experiments under these conditions. This is the operating principle of the SAF diffuser. A buoyantly induced flow is created by injecting bubbles into a stagnant water body. Ramanathan and Arndt (1994) have shown that the induced velocity can be calculated by:

$$F_{rw} = \frac{V_w}{\sqrt{L_e g}} = \left[ \frac{2\alpha}{(1-\alpha)K} \right]^{0.5}$$

where $K$ is a loss factor involving the frictional flow losses in the tube (see Ramanathan and Arndt, 1994 for details). Ramanathan and Arndt (1994) have developed expressions for determining this loss factor.
a. Bubble formation by buoyancy alone.

\[ d_b \approx 1.8 \left( \frac{\sigma d_0}{\rho g} \right)^{1/3} \]

b. Bubble formation enhanced by fluid dynamic drag.

\[ d_b \approx d_0 \left( \frac{V_a}{V_0} \right)^{1/2} \]

Figure 2. Bubble formation.
\( \alpha \) is the void fraction defined as the ratio of the volume of air in a given volume of water. An empirical correlation is necessary for determining void fraction, \( \alpha \), as a function of the volume flowrate, \( Q_a \), of air admitted to the diffuser. Ramanathan and Arndt (1994) found:

\[
\alpha = c_r (F_r)^{2/3}
\]  

(4)

where the primary parameter is air flow Froude number:

\[
F_r = \frac{4Q_a}{\pi D^2 \left(gL_w\right)^{0.5}}
\]  

(5)

Equations (2), (3), and (4) are the primary design equations for the SAF diffuser. \( V_0 \) and \( V_w \) are related by the geometry of the diffuser. \( V_a \) is controlled by the air flowrate, \( Q_a \), and the size and number of orifice holes.

The distribution of bubble sizes in the plume discharged from the upper end of the diffuser is a function not only of the bubble size at formation, but also on coalescence and breakup processes within the tube.

In the case of conventional diffusers, most of the mass transfer occurs in the bubble plume. In the SAF diffuser, mass transfer occurs within the tube and in the bubble plume. Several parameters have been developed for the evaluation of diffusers. One of the most important criteria is the Standard Aeration Efficiency, SAE, which is defined as the oxygen transfer rate normalized to power input, \( \text{kg} \text{O}_2/\text{KwHr} \). The oxygen transfer rate is defined as mass of oxygen per unit time that is dissolved in a volume of water when the initial concentration of oxygen is zero (ASCE, 1984). The SAF diffuser was found to be capable of power savings as high as 40%, but practical implication of this concept requires further study. Thus study is the first step in that direction.

1.4 MEASUREMENT PRINCIPLES

The same measurement principles were used in both the laboratory studies and the field investigations. Oxygen transfer measurements were carried out using a dissolved oxygen probe according to the 1984 ASCE standard. The important measure of diffuser performance is the mass transfer coefficient, \( K_{LA} \) which is defined by the transfer equation

\[
\frac{dC}{dt} = K_{La} (C_a - C)
\]  

(6)

On integration the above equation gives

\[
ln \left[ \frac{C_a - C}{C_a - C_0} \right] = -K_{la} t
\]  

(7)
where
\[ C = \text{effective average DO concentration in the liquid phase at any time } t \]
\[ C_s = \text{dissolved oxygen saturation concentration (concentration at infinite time)} \]
\[ C_0 = \text{DO concentration at time zero} \]
\[ K_{L_a} = \text{volumetric mass transfer coefficient (1/time)} \]
\[ t = \text{time} \]

The model assumes a completely mixed liquid with a uniform DO concentration throughout the tank. The resulting \( K_{L_a} \) value obtained from a non-linear fit of the DO concentration versus time data was multiplied by the tank volume to arrive at the \( K_{L_A} \) value.
II. DESIGN ISSUES FOR SAF DIFFUSER OF RECTANGULAR PLANFORM

A prototype device was designed based on a study of Minnesota Aquafarm's (MAF's) present aeration needs and from research results on SAF diffusers with circular planforms performed at SAFHL. This research was compiled in a report by V. Ramanathan and R. E. A. Arndt (1994). Where pertinent, the page number of that report will be given in the following references.

Based upon the results of this research, an initial rectangular planform prototype diffuser was created. Due to the scope of this study, four design parameters were chosen to be studied in the laboratory before constructing the final diffusers. These parameters were:

a) the number of rows of orifices,
b) the width of the mouth,
c) the width of the tube, and
d) the height of the tube.

Other parameters were fixed and not altered during the study on the prototype device. These were air flowrate, horizontal length of the rectangular planform, orifice diameter, and orifice hole pattern.

One goal of this project was to provide a cost efficient alternative to MAF's present aeration system. Therefore, consideration was given to the cost of manufacturing the final device should MAF decide to use the SAF aerator in the future. Therefore, designs which required expensive custom manufactured parts, such as injection molds or dies, were avoided. Only materials and equipment readily available on a commercial scale were chosen.

2.1 DESCRIPTION OF CURRENT MAF AERATOR

The MAF aerator is supported on an 8' x 20' rectangular frame welded from 1 5/8" wide steel unistrut (figure 3). A 2" diameter air supply line is attached along the edge of one 8' length. From the supply line 24 hoses (0.5" I.D.) run down the 20' length of the frame, overlap an iron bar on the other side and return down the 20' length yielding a total of 48 lengths of hose crossing over the frame. Along one horizontal side of each hose are 0.5" wide slits spaced 1.5" apart; when the air supply pressure becomes sufficiently high, the air escapes through the slits to aerate the water. The operating air flowrate was estimated between 50-80 scfm.

In order to design a cost effective replacement aerator for the MAF aerator, it was decided to design the SAF aerator to fit upon the same 8' x 20' rectangular unistrut frame and to operate at the same air flowrate as the MAF aerator. In this way the SAF aerator could be easily replace the MAF aerator without changing other design equipment such as blowers, dock support frames, or air supply lines. This also provided for an easier method to compare the performance of these two types of aerators.

The terminology "aerator" will be used in this report to refer to the entire 8' x 20' aeration platform for either the MAP or SAF aerators. The SAF aerator was initially
Figure 3. MAF aerator with 48 slitted hoses (0.5" I.D.) tapping into air supply.
constructed from 60 individual aeration units, each of which will be referred to as a "diffuser". An "aeration unit" will refer to a single 8 ft length of the final aeration device comprising of six diffusers.

2.2 KEY DESIGN PARAMETERS FOR THE SAF DIFFUSER

Based on the studies of circular planform diffusers, the key parameters to study for the rectangular planform were determined to be a) the tube height, b) the tube width, c) the mouth (or inlet tube) width, and d) the number of rows of orifice holes. Other parameters were fixed either due to the inaccessibility of commercially available materials or due to the minor impact on the overall performance of the diffuser. Another consideration was the time involved to manufacture each section of the diffuser. Although it may not have been difficult to perform a given procedure for a single prototype, replicating that procedure for the final 60 diffuser units chosen for the field study could have proven to be an awesome task.

2.2.1 Orifice Diameter & Hole Pattern

Both time and cost ruled out the possibility of drilling the number of orifices necessary for 60 diffusers. Therefore, a company was sought which could perforate holes within the 0.5–1.0 mm diameter range studied with the circular planform. One company was found which could provide hole diameters as small as 0.84 mm (0.033") in the staggered row pattern desired. These holes were punched into soft brass sheets 0.016" thick with 12" wide rows, and sheet lengths of 96". The center-to-center distance between the holes in each row was 0.112". The distance between one row and the next was also 0.112", with the hole pattern staggered between the rows (figure 4). There was a 0.125" distance between the holes from one row to adjacent holes in the next row (i.e. 0.125" apart on the length of the triangle).

2.2.2 Length

Based on the availability of the perforated brass sheet, the horizontal length, \( L_3 \), of the rectangular planform was set at 8".

2.2.3 Number of Diffusers

At this point an educated guess was made as to how many diffuser units would be necessary to aerate the plan area used in the field study. With the above initial dimensions, one rectangular diffuser 8" was projected to be able to perform nearly equivalently to four circular diffusers. Since four circular devices performed equivalently to one 7" dia. stone dome diffuser unit, the kind typically used in waste water treatment, one rectangular diffuser should perform equal to one 7" stone diffuser (Ramanathan and Arndt, 1994, p. 111). In waste water treatment facilities there is a rule of thumb for number of diffusers necessary: aim to cover 5–20% of the floor plan area with 10% a typical value, and use 0.26 sq. ft. as the calculation value for the area of a 7" stone diffuser (Mike Rieth, 1995). So given a 8' x 20' platform for the field study (160 sq ft), 10% of the floor plan area = 16 sq. ft. Dividing 16 by 0.26 results in 61.5 stone diffusers necessary for the plan area. Therefore, it was decided upon manufacturing 60 rectangular diffusers 8" long.
Figure 4. Orifice staggered row pattern for perforated brass sheets.
Note, it was taken into account that more diffusers would be necessary for waste water treatment than for aerating the cleaner lake water at the fish farm site. The actual plan area to aerate at the fish farm was greater than the aerator platform. The plan area was 25' x 25' or 625 sq ft; thus only 1/4 of the diffusers used in typical waste water treatment would be used in these lake water aeration tests.

2.2.4 Air Flowrate

In order to compare the performance of the SAF aerator to the MAF aerator the same air flowrate was used for each aeration system. However, the air flow through the MAF aerator had never been precisely quantified beyond a range estimate of 50–80 scfm. Therefore, 80 scfm was chosen as the field test flowrate. Given 60 diffusers, this resulted in 1.33 scfm (627 cc/s) per diffuser. With this in mind, all lab tests were performed at 1.33 scfm ±0.2 scfm.

2.2.5 Number of Orifices

To estimate the number of orifice holes required, studies on the circular planform showed that maintaining an air flowrate < 1.0 cc/s through each orifice was required to achieving a bubble diameter less than 4 mm (Ramanathan and Arndt, 1994, p.20). The lower the air flowrate below 1 cc/s, the smaller the resulting bubble diameter obtained. As a rule a bubble diameter of ~2 mm is considered optimal for oxygen transfer.

For the best oxygen transfer rate, the circular device had 432 holes—27 holes /row and 16 rows (Ramanathan and Arndt, 1994, p. 83). Since 4 circular devices were approximately equivalent to one rectangular device, approximately 1728 holes (4 x 432) would be sufficient. Given the hole spacing of 0.112" on the perforated brass sheet, each 8" row had ~71 holes. Twelve rows would provide 852 holes for each half of the rectangular diffuser. Multiplying by 2 resulted in 1704 holes per rectangular device. This resulted in an air flowrate of 0.367 cc/s per orifice, which was anticipated to yield bubble diameters in the 2–3 mm range.
III. CONSTRUCTION OF DIFFUSERS & AERATOR UNITS

3.1 MATERIALS USED

Identical or similar materials were used in constructing the lab prototype diffuser as were used in creating the aeration units used in the aeration platform for the field study. PVC plastic was used entirely in the construction of the final aeration units, chosen for its ease of procurement and weldability. Tube walls were created from 1/8" thick schedule 40 gray PVC. They were welded to the plenum and to each other using a plastic welding kit and gray PVC welding rod.

3.2 PLENUM

2.5" x 2.5" x 8' long PVC smooth gutter drain pipe commercially available at local hardware stores was used in constructing the aeration unit plenums (figure 5a). On one side of each pipe, six slots, 8" long x 1 3/8" wide, were cut out. The slots were cut 8" apart starting 4" in from one end of the pipe. The slots were cut starting 0.5" down from the top edge of the pipe. A 1/2" bead of Vulkem® waterproof bonding sealant was gunned around each slot and flattened with a putty knife. Then the perforated brass sheet was placed over the slot as described below.

3.3 ORIFICES

Perforated brass sheets, 12" wide x 96" long, with 0.033" dia. holes spaced 0.112" apart in staggered rows with 0.125" across the triangle were obtained from Clark Perforating Co. in Milan, MI. Then the sheet was sliced into 4.5" lengths which were initially 12" wide. The width was reduced to 10" and a 1" wide strip along each of the 10" edges was bent at a 90° angle.

This bent brass sheet was placed over the slot and 6 sheet metal screws were screwed through the brass into the top and bottom sides of the plenum to hold the brass sheet tightly to the slot (figures 5b, 5c). Excess Vulkem® which oozed through the perforations was removed. In this manner each side of the diffuser plenum was created.

3.4 TUBE WALLS

Along the top of the 8' length of the plenum pipe, 1/8" thick PVC boards, 7" tall, were mounted and plastic welded into place (figure 6a). Then two plenum pipes were brought together with the secured brass sheets facing each other. PVC sheets, 1/8" thick, were placed at both end of the slots and welded into place (figure 6b). They acted as a crossmember tube walls joining the two 8' plenums and separating the brass covered slots into six diffusers.
a. Step 1: Cut 6 slots into an 8 ft long rectangular pipe which will be used as a plenum.

b. Step 2: Place perforated brass sheet over slot

c. Step 3: Add 6 screws to hold brass sheet in place

Figure 5. Construction of Plenum with Orifices
a. Step D: Plastic weld on a tube's outer wall.

b. Step E: Line up two plenums face to face and weld in crossmember tube walls to separate individual diffuser units.

Figure 6. Construction of the tube walls
Figure 7. Step F: Construction of aerator base and end plugs.

- Shims (1/8" thick) glued in between diffusers across both plenums to join them together.
- 0.5" thick aerator mouth entrances with rounded edges glued to the shims.
Underneath the plenums between the diffusers, 2" wide shim strips were glued with Weldon® brand PVC cement across both plenums, thereby joining them together (figure 7). On the underside of the shims, the entrance pieces to the mouth were glued to the shims. These entrance pieces were made from 1/2" thick schedule 40 gray PVC which had both 8' edges rounded with a 90° corner router bit. A 100% silicone sealant was used to fill in the crevices between the plenum and the entrance pieces. Also, each end of the plenum pipe was plugged with a 2.5" x 2.5" square PVC block, 0.5" thick. Finally, air taps were placed in the sides of each plenum near the center of the 8' length, 1" down from the top edge of the plenums.

3.5 ALTERNATIVE MATERIALS USED IN LAB PROTOTYPE

In the prototype device, the plenum was constructed from the same rectangular PVC pipe as the final device. But the outer tube walls were made from polyethylene and the crossmember walls from clear polycarbonate to allow visibility into the diffuser as it was operating. The tube walls were connected together via tap screws and silicone sealant. In this manner the bubble formation and water flow field could be observed and the wall heights and widths easily adjusted for various tests.

3.6 ALTERNATIVE CONSTRUCTION USED IN LAB PROTOTYPE

The prototype was 22" long with only one 8" long brass covered slot on each side located in the center of the length of each pipe (i.e. only one diffuser instead of the six in the field units). Since the perforated brass sheet for the field aerator units was unavailable at the time of the prototype's construction, the brass sheets themselves were drilled on a mill according to the same design pattern of the perforated brass sheet. A 1/32" (0.03125") diameter drill bit was used. Also, air taps were placed on one end of each plenum through the 2.5" x 2.5" plugs.
IV. LABORATORY TESTING

4.1 EQUIPMENT AND CHEMICALS

All equipment and chemicals used in the laboratory tests are listed in Appendix A.

4.2 SETUP

The tests were carried out in a rectangular test tank of 112 cm x 112 cm planform, and filled with municipal drinking tap water to a height of 137 cm (figure 8). This yielded a total water volume of 1700 L after accounting for the volume displaced by equipment in the tank. The prototype diffuser was centered in the tank with its bottom surface supported 26 cm up from the tank floor. Four aquarium heaters were positioned in the tank to maintain the water temperature at 20°C ±0.5° C. One heater was attached to each tank wall horizontally at a height of 30-40 cm up from the tank floor. The tank was also insulated on the outside with 1" thick Styrofoam to prevent temperature fluctuations.

4.2.1 DO & Temperature Measurements

Three probes were placed in the tank: two to measure temperature and one to measure DO concentration. Each probe was located in a separate corner of the tank, equidistant from the aerator and that corner. The temperature probes were suspended 45 cm and 90 cm, up from the tank floor, respectively. The DO probe was suspended 35 cm up from the tank floor. During initial testing the DO probe was moved to various positions in the tank. Since the same DO reading could be observed throughout the tank, it was well mixed and the DO probe was not moved during any further lab testing.

4.2.2 Regulation of Air Flowrate

Air was supplied from the house compressor line. It was regulated to provide 16 psi outflow which passed through two filters to remove any excess moisture, oil, and particulates. Then a needle valve was used to set the air flowrate going through a rotameter to 1.25 cfm (yielding 1.33 scfm). At the exit of the rotameter the temperature and pressure were read to correct rotameter readings to scfm. A six foot length of 3/8" I.D. vinyl tubing was used to bring the air to the diffuser in the tank. A Y-shaped connector was used at the diffuser to split the air flow to each side. There was very little fluctuation in air flowrate, generally ±0.01 cfm, throughout any given test.

4.2.3 Measurement Procedure

Diffuser performance was measured using the standard ASCE procedure (ASCE, 1984). Cobalt chloride was used as a catalyst for the sodium sulfite to remove oxygen from the water. For each test 0.85 g ±0.05 g of cobalt chloride were weighed and dissolved in
Figure 8. Schematic of Laboratory Experimental Tank

W = water & particle filter
O = oil filter trap
PR = pressure regulator
V = needle valve
R = rotameter
TP = temperature probe
P = pressure gauge
DT = diffuser tube
DO = DO probe
S = stand
H = aquarium heater
WCP = water circulating pump
100 mL prior to adding to the test tank. This provided a cobalt concentration of 0.5 ppm. A water pump was used to mix the chemical in the tank. The inlet hose was located in one corner of the tank and the outlet hose in an opposing corner (kitty-corner). Air was also pumped through the diffuser to aid mixing. The cobalt chloride was allowed to mix for a minimum of 15 minutes prior to adding the sulfite solution.

Sodium sulfite was the deoxygenating chemical used in each test. Sulfite binds with dissolved oxygen to form sulfate, thereby removing the oxygen from the water. For each test 140 g ±10 g of sodium sulfite was weighed and dissolved in a 7 liter jug sample of tank water prior to adding to the tank. This provided a sulfite concentration of 82 ppm. The air line to the diffuser was temporarily shut off when the sulfite solution was poured into the tank. The water pump was used to mix the sulfite throughout the tank. When the DO concentration dropped to below 0.5 mg/L, the air flow was turned back on.

After cobalt chloride had been added for one test, it did not need to be added for following tests. When replicate testing was performed only 140 g of sulfite solution was added at the start of the replicate tests. Generally, only two replicates were performed before the tank was drained to modify the diffuser unit for further testing. No more than four tests were ever performed before the tank was drained. Each time the tank was drained it was refilled with fresh tap water and new cobalt chloride solution was added to it.

4.2.4 Recording & Analyzing Data

After adding the sulfite, three Styrofoam boards (1" thick) were floated on the water surface to minimize air-water surface mixing. Water temperature and air line temperature & pressure were recorded at the start of each test and generally at the end of each test as well.

The DO meter was connected to a data logger which logged the DO concentration in mg/L once every minute. The tests ran until >98% saturation was achieved. This occurred in less than four hours for all tests.

The DO concentration versus time data was transferred to a computer where it was edited to 96 data points. In the computer analysis, DO values from every minute of the first 80 minutes were used and also DO values for the following minutes: 85, 90, 95, 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200, and 240. These values were input into ASCE's ASCE 87 computer software program designed for non-linear estimation of unsteady state oxygen transfer. The software estimated the $K_LA$ value based on the DO and time data provided. Up to 100 data points could be supplied with each data set analyzed. The resulting $K_LA$ value was multiplied by the tank volume to arrive at the $K_LA$ value.

4.3 PARAMETERS VARIED IN LAB EXPERIMENTS

4.3.1 Tube Width and Mouth Width Ratio

The initial selection of tube height ($L_2$), tube width ($D_p$), and mouth width ($D_{op}$) were based on a circular planform with a 2" diameter mouth. The ratio of the cross-sectional areas of the tube to the mouth, $A_p/A_{op}$, was found to be an important parameter in the circular device with an optimum in the range of 2.4–3.0 (Ramanathan and Arndt, 1994, p.88). Therefore, the $A_p/A_{op}$ ratio for the rectangular device was set at 2.5. Three mouth widths were studied, 2", 1", 0.5". Given a 2" wide mouth, the tube width was set to 5" to
maintain a $A_p/A_{op} = 2.5$. A few studies were also carried out with different tube widths independent of mouth width.

4.3.2 Tube Height

Previous studies with circular devices with an area ratio of 2.5, indicated that the optimum effective tube height, $h_e$, was 3". Therefore, tube height was varied from 0–7" in these studies.

4.3.3 Rows of Orifices

During the final lab tests the number of rows of orifice holes was decreased from 12 rows to 8 rows and finally to 4 rows to examine the effect on the oxygen transfer rate.

4.4 RESULTS OF LABORATORY STUDIES

Table B1 in Appendix B lists the results of all the tests performed in the laboratory. A minimum of two replicate runs were performed at each test condition. Figure 9 gives a graph of the effect on $K_L A$ by varying the tube height under various tube & mouth widths.

It is clear from figure 9 that with taller tube heights, larger $K_L A$ values were obtained. The best tube height was also the maximum tube height tested, i.e. 7". It is not known whether or not any significant gain could have been achieved by increasing the tube height further. The data indicates the $K_L A$ value tapered off near the 7" tube height in all cases, except the case of a 4" tube & 1" mouth width. There were not enough data points in that case to confirm or negate this issue.

The tube-to-mouth cross sectional area ratio, $A_P/A_{op}$, was not found to be optimal at 2.5, as was observed for the circular planform. However, the data did show that decreasing the mouth width causes an increase in $K_L A$ in all cases except the data for a 2.5" tube & 1" mouth width. In this latter case the distance, $D_v$, from the mouth edge to the tube wall was the shortest.

The $K_L A$ values for 4, 8, and 12 rows of orifices were 873, 898, and 870 respectively. The variance between these values could be within experimental error. Therefore, it was inconclusive whether or not a diffuser with 8 rows of holes would have performed significantly better than one with 4 or 12 row of holes.

4.5 DISCUSSION

It was found that increasing the tube height also increased the rate of oxygen transfer. This indicates that much of the oxygen transfer is occurring while the bubbles are in the tube. This is probably due to the fact that the bubbles are nearest their optimum diameter for oxygen transfer while inside the tube. As the bubbles rise they grow larger due to a decrease in the hydrostatic pressure. Both of these factors have a negative effect on oxygen transfer.
Figure 9. $K_L A$ values for various rectangular prototype diffuser dimensions.

Figure 10. Vortex mixing in diffuser tube.
Better oxygen transfer rates were achieved with narrower mouth widths. What occurs when the mouth narrows is an increase in the water velocity and flowrate through the mouth of the diffuser. This in turn provides a greater shear force to "cut-off" bubble formation faster and make them smaller, approaching the optimum diameter. With the wider mouth, the flow velocity is slower and the bubble sizes are somewhat greater than the optimum bubble diameter.

When the distance, $D_V$, from the edge of the mouth outlet to the tube wall was decreased, there was a corresponding decrease in the oxygen transfer rate. In all the tests where $D_V = 1.5"$, vertical vortex mixing was visibly observed to occur in the tank (see figure 10 on previous page). When $D_V$ was decreased to 0.75" there was a dramatic reduction in the amount of eddies or vortices observed with commensurate reduction in performance. This vortex aids in oxygen transfer possibly by increasing the bubble residence time for oxygen transfer at optimal bubble size.

The lack of difference in $K_L A$ values between 4 and 12 rows of orifices holes suggests that most, if not all, of the air supplied to the diffuser is escaping through the top 4 or fewer rows of orifice holes. Visual observation of the aerator confirms this, since the bottom third to one-half of the plenum remained full of water during all aeration tests.

This is due in part to the very low pressure drop across the orifices. Air easily escapes through a few rows of holes at this flowrate and does not force the air out of the lower half of the plenum because the internal pressure in the upper plenum is not great enough to overcome the hydrostatic force against it. In order to increase the pressure drop across the orifices and to cause more rows of holes to be utilized, the air flowrate would have to be increased significantly, the number of orifice holes within each row decreased, or the diameter of the orifice holes dramatically reduced. This implies that the optimal performance for this configuration would occur at higher air flowrates.
V. FIELD STUDY

5.1 AERATOR UNIT DESIGN PARAMETERS

Aerator units were manufactured at the St. Anthony Falls Hydraulic Laboratory and transported to Chisholm, Minnesota where they were compared to Minnesota Aquafarm's present aeration system. Based on the lab studies, the dimensions chosen in constructing the 8' long field aerator units were as follows:

- The tube height, \( L_2 = 7" \)
- The mouth width, \( D_{op} = 0.75" \) (0.5" was too small to construct easily)
- The tube width, \( D_p = 3.75" \)
- The distance from the mouth edge to the tube wall, \( D_v = 1.5" \)
- Number of rows of orifices = 12, with 1702 orifices per diffuser.

Each aerator unit weighed on average 35 pounds. Lab studies indicated that one unit operating at an air flowrate of 8 scfm, required approximately 25 pounds of excess weight to overcome the buoyancy of the aerator.

5.2 FIELD AERATOR SETUP

5.2.1 Equipment & Chemicals

All equipment and chemicals used in the field tests are listed in Appendix A.

5.2.2 SAF Aerator Platform

Ten 8' SAF aerator units were built. Each unit contained six SAF diffusers yielding a total of 60 diffusers for the 8' x 20' platform (figure 11). Each aerator unit was attached to the unistrut frame by means of 3" long unistrut pipe clamps around each end. The aerators were spaced approximately 2 feet apart. Both plenums on each aerator unit were tapped at the 4' center in order to supply air to the diffusers. The taps were centered 1" down from the top surface of each plenum (thus giving a value for \( L_1 = 1.0" \)).

The 2" air supply line ran down the 20' length of the frame on one side of it. Ten 0.75" I.D. taps were placed in the supply line. Each tap was then connected with a tee which split the air flow down each side of the aerator unit to the plenum tap. Vinyl tubing (0.5" I.D.) was used to supply air from the tees to the plenums.

5.2.2 Test Tank

In order to compare the SAF and MAF aerators, a test tank was constructed by sewing together waterproof blue poly-tarps—the type used as tent ground cloths and covering log piles (figure 12). The upper portion of the tank encompassed a square area,
Figure 11. Plan-view of SAF Aerator Platform: 10 SAF aerator units of 6 diffusers each. Air is distributed to the center of each unit on both sides. $\alpha$, $\beta$, $\gamma$, and $\delta$ are the diffusers where pressure taps were placed on each side numbered 1 & 2.
24' x24'. The sides went down 10' deep, the bottom of the tank was terminated by an inverted pyramid. The length from each corner of the pyramid's base to the peak was approximately 30'. The total estimated tank volume was 10,000 cubic feet.

The enclosure was placed in the center of a 25' x 25' enclosed floating dock. In each of the corners at the 10' depth at the tip of the pyramid, 30 pound cement weights were hung to keep the tank expanded. The tank walls were lifted out of the water by approximately a foot to prevent water from mixing between the tank and the rest of the lake water.

After each test the oxygenated water in the tank was replaced with fresh lake water having a lower DO concentration. This was carried out in two steps. First, the tank walls on two sides were lowered and the tip of the tank pyramid was lifted with an attached rope to flush water out of the lower tank depths. Second, a 660 gpm Kasco pump used to flush out remaining oxygenated water with new lake water. The pump was allowed to operate for a minimum of 4 hours. The tank pyramid tip was then allowed to settle back down to the bottom allowing the tank to refill.

Refilling the tank with fresh lake water worked exceedingly well. After the procedure the DO concentrations inside the tank were equivalent to lake DO measurements. Also, from the previous tank aeration test no background fluorescein levels were detected when water samples were returned to the lab (see measuring tank volume below).

5.2.3 Placement of SAF & MAF Aerators

Both the SAF and MAF aerator platforms were placed within the tank, side-by-side (figure 13). Testing was performed on one aerator at a time while the other remained idle, but remaining in the test tank. The MAF aerator platform was set to a depth of 10' 3" so that the tube slits where the air bubbles were formed were at the 10' depth. The SAF aerator platform was set to a depth of 10' 4" so the center row of the 12 rows of orifices was at the 10' depth. These depth settings were performed by using a marked aluminum rod, 1" thick. Each aerator was suspended to the dock via 4 ropes, 1/3 and 2/3's down the two 20' side lengths of each frame.

Weights were added to the lines supporting the aerator platforms to overcome buoyancy. The weights hung down below the platforms. The MAF and SAF aerators required ~90 lbs and ~240 lbs, respectively, to overcome buoyancy.

5.3 MEASUREMENT PROCEDURES

5.3.1 Effective Tank Volume

Since the test tank was not a rigid structure, the tank volume was measured during each field test by adding a known quantity of fluorescein, a fluorescent chemical. The chemical was allowed to mix in the tank during the aeration test. Water samples were taken at the end of each test and often at other times during aeration as well. These water samples were returned to St. Anthony Falls Hydraulic Laboratory where the concentration of fluorescein in each could be measured by using a fluorometer. (Note, a tank water sample was also taken prior to fluorescein addition in each test, in order to account for the background fluorescein level.)
Figure 12. Tarp Bag Tank Enclosure—estimated volume 10,000 cu. ft.

Figure 13. Planview of Dock setup: side-by-side aerator comparison
By knowing the original quantity of fluorescein added, and the final fluorescein dilution, the tank volume could be calculated. This analysis assumes that the fluorescein was completely mixed throughout the tank when the water sample was taken. It also assumes there were no leaks in the tank bag so that no mixing with outside lake water occurred.

During the first four initial studies, field tests A–D, ~5 g of fluorescein were dissolved in a 2 gallon jug and added to the test tank. During the final studies, field tests E–J, a fluorescein solution of 12 grams was first dissolved into 12 liters. Then 1.00 liter of this solution (~ 1 gram) was added per test. The original solution's concentration was also measured on the fluorometer. It could not be determined which of these methods is a more accurate determination of the tank volume.

5.3.2 Air Flowrate

Air was supplied by one compressor for all but field test H, where two compressors were used in parallel. The backpressure on the compressor(s) was set approximately 50 psig via a lever valve on the airline. Downstream from this valve an orifice plate was used to measure air flowrate. The gauge pressure between the valve and the orifice plate was measured with a 15 psi differential pressure transducer. The pressure drop across the orifice plate was measured with a 1 psi differential pressure transducer. These transducers were linked to a data logger which recorded the pressure differentials every 5 minutes.

5.3.3 Pressure Drop Across Diffuser Orifices

The pressure drop across the orifices in four diffusers were measured. The diffusers chosen were labeled α, β, γ, and δ. One of each was located near each corner of the aerator platform. Both plenums in each diffuser were measured and numbered 1 & 2 for convenience (refer back to figure 11).

A pressure tap was placed in the top of the plenum between the air supply tap and the diffuser orifices. This pressure tap was connected to one side of a 1 psi differential pressure transducer via 3/16" vinyl tubing. From the other side of the transducer another 3/16" vinyl tube went down the outside side of the plenum with an opening at the 1" depth from the top of the plenum. This opening was at the 5th row of orifice holes from the top row. Therefore, when both lines were purged and attached to the pressure transducer, the differential pressure which was recorded gave the estimated pressure drop across the orifice holes at the 5th row which was considered an average value.

5.3.4 DO Concentration

For initial field tests, A–D, three DO probes supplied by Minnesota Aquafarms were used and placed near the surface, at 10' and at 20-24'. DO concentrations were logged manually every five minutes for every test. Not all of the probes were operating properly for each test. Therefore data from the most reliable probes were chosen in calculating K_LA values and these values were averaged.
Upon returning to the fish farm after modifying the SAF aerator units (see below), it was decided to bring one of SAFHL's DO meters and probes with a stirrer unit. The DO probe was positioned 10' under water in a corner away from the aerator being tested. A datalogger was also brought with the DO meter and DO measurements were logged once per minute during the remaining tests. Although DO data from the MAF probes were also logged manually every 5 minutes, the SAF DO probe proved to provide much more reliable values. Therefore, for field tests E–J, only results using this probe are presented here.

Depth profile data for the field tests were recorded using a YSI 51B DO meter supplied by MAF. This meter gave an analog scale readout. The probe operated with an accuracy of approximately ±0.2 mg/L DO.

5.3.5 Temperature

Two temperature probes were supplied by MAF and were placed at the surface and at 10'. A temperature meter & probe supplied by SAFHL was used to measure air line temperatures, depth profile temperatures, and to cross-check the accuracy of the MAF temperature probes. All temperature probes performed to within specifications.

5.3.6 BOD

The BOD will remove oxygen from a water body. If the BOD is not accounted for erroneously low $K_{L}A$ values will be reported. Therefore, the BOD was measured by filling a 8 liter Nalgene® plastic jug completely full of lake water. The DO concentration was measured by inserting SAFHL's DO probe into the jug. Then the jug was sealed without any visible air bubbles present. The jug was wrapped in a black plastic bag to prevent photosynthesis, and then was suspended in the lake to maintain the same temperature as the lake water. After a period of time the DO concentration in the jug was remeasured. This test was performed for four time periods. The periods were 4, 11, 25, and 20 hours.

5.3.7 Photosynthesis

Photosynthesis will contribute the overall dissolved oxygen content of a water body. Since photosynthesis by algae will add dissolved oxygen to the lake, during any test conducted in daylight the test tank was covered with a 30' x 40' opaque blue plastic tarp. This tarp went over the dock railing and was kept off the water to prevent heat transfer. This eliminated all concerns of erroneously high $K_{L}A$ values due to photosynthesis.

5.4 INITIAL PROBLEMS ENCOUNTERED

Several unanticipated hindrances occurred during the initial field studies which are important to document. First of all, a high volume blower (up to 550 cfm) was originally scheduled to supply the air; but the blower unit required some repairs which could not be made in time for this study. Therefore, the above mentioned compressor units were chosen for the study. This was unfortunate because the blower would have afforded the opportunity to run tests at higher air flowrates. As it was, the tests were restricted air flows of 38 and 76 scfm for all tests. Most tests were performed at 38 scfm because one of the two compressors was needed by fish farm employees some of the time. Therefore, the
SAF aerator which had been optimized in the lab to operate at 80 scfm, was tested under sub-optimal air flowrates.

Secondly, the dataloggers which were being supplied by Minnesota Aquafarms were not working. Also, there were some difficulties with the dissolved oxygen probes. Initially, too much electrical interference caused them to remain inoperable. It was difficult to get them calibrated correctly and they needed good water flow in order to read properly. Finally one of them quit working altogether.

Thirdly, after some initial field testing studies on the original SAF aerator design it became apparent that an air distribution problem existed within each aerator unit. Due to the low pressure drop across the orifice holes most of the air was exiting the diffuser highest in elevation (i.e. nearest the surface of the lake with the lowest outside hydrostatic pressure). So instead of having 60 diffusers operating within 10 units, only one diffuser, at best two, were operating within each unit. This may have been less of an issue if the aerator platform could have been anchored to a cement bottomed tank where it could have been maintained completely level. If the air flowrate had also been an order of magnitude or so higher, or the orifice hole diameters had been much smaller, then a larger pressure drop would have occurred across the orifices causing the air flow to distribute more evenly down the plenum. This possibility would have to be considered in concert with other possibilities.

Two configurations of the aerator platform were tested during these initial studies. One was with all 10 of the aerator units and another was with only 5 of the aerator units. The purpose of operating only 5 aerator units was to double the air flowrate through each unit to overcome the sub-optimal air flow delivered by one compressor. In reporting results these two configurations will be distinguished by subscripts. "SAF5" will refer to the configuration with only 5 aerator units, and "SAF10" will refer to the 10 aerator unit platform.

5.5 MODIFICATIONS TO SAF AERATOR DESIGN

Due to the above mentioned difficulties, the aerator units were returned to SAFHL and modified. The plenums in each 8' unit were opened and sealed so that 3 individual diffusers were created (figure 14). This resulted in a total of 30 diffusers for the 10 aerator units as a whole. In reporting results, this modified aerator configuration will be referred to as "SAFm" when it was tested at the base air flowrate with one compressor. When two compressors were used in this configuration, "SAFm2" will be used to indicate this difference.

With the aerator units modified in this manner no extra weight was necessary to overcome buoyancy. Using only 30 diffusers brought the air flowrate through each diffuser within lab design parameters when using one compressor delivering air at 38 scfm.

Each 8' aerator still had one tap into the 2" air supply line. Again, the air flow from the tap was split into two 0.5" I.D. hoses, each running down the outside of one plenum. Tee connectors distributed air from these 0.5" I.D. hoses to each individual diffuser via 0.25" I.D. hose. The air flow ultimately had to squeeze through a 0.125" I.D. tap connector at each plenum. This created a slightly larger pressure drop from the supply line to the plenums and therefore distributed the air flow much more evenly.
a. Original SAF aerator unit.

b. Modification: eliminate 3 diffusers.

c. Modified SAF aerator unit: 3 individual diffusers with air distributed to each.

Figure 14. Modifications to SAF aerator units.
5.6 DATA ANALYSIS

5.6.1 Estimating KLa

Just as in the lab tests, the DO concentration vs. time data were edited and input into ASCE's ASCE 87 software program which estimated KLa. Since these tests were not performed at 20° C, the following temperature correction factor was employed:

\[ K_{La_{20}} = K_{La} \cdot \theta^{(20-T)} \]  

(8)

where \( K_{La_{20}} \) = KLa value corrected to 20° C; \( \theta = 1.024 \); and \( T \) = temperature in °C.

Then the \( K_{La_{20}} \) value was multiplied by the estimated tank volume to give the KLa value reported in cc/sec.

5.6.2 Calculating SOTR

The standard oxygen transfer rate, SOTR, was calculated from the estimated values for KLa as follows:

\[ \text{SOTR} = K_{La} (C_{ss}) \]  

(9)

where \( C_{ss} \) = the DO saturation concentration at 20° C and 1 atm; this value was taken as 9.07 mg/L based on the oxygen solubility table given with the YSI model 58 DO meter operating instructions.

The units of SOTR are given in kg/sec.

5.6.3 Calculating SAE

The standard aeration efficiency, SAE, was calculated as follows:

\[ \text{SAE} = \text{SOTR/power input (kilograms/kilowatt hr)} \]  

(10)

where power input in watts is calculated as follows:

\[ \text{power input} = \frac{wRT_1}{K} \left[ \left( \frac{P_2}{P_1} \right)^K - 1 \right] \]  

(11)

where

\( w \) = mass flowrate of air (kg/sec)
\( K \) = gas constant = 287 Nm/kg•Kelvin
\( T_1 \) = absolute temperature before compression in degrees Kelvin
\( P_1 \) = absolute pressure before compression
\( P_2 \) = absolute pressure after compression
\( K = (k-1)/k \), where \( k \) = ratio of specific heats for air = 1.4
5.6.4 Field Tests Performed

The following table (1) lists the tests performed at the fish farm site. The tests were name "A", "B", etc. so they could be easily referred to during the discussion. (Note: the letter "I" was skipped on purpose to avoid confusion with the number 1 in naming field tests).

```
<table>
<thead>
<tr>
<th>Field Test</th>
<th>Aerator Tested</th>
<th>Aerator Platform Configuration</th>
<th>number of compressors</th>
<th>Air Flowrate scfm</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>MAF</td>
<td>48 slitted hoses</td>
<td>1</td>
<td>36.9</td>
</tr>
<tr>
<td>B</td>
<td>SAF5</td>
<td>5 aerator units each with 6 diffusers</td>
<td>1</td>
<td>38.0</td>
</tr>
<tr>
<td>C</td>
<td>SAF10</td>
<td>10 aerator units each with 6 diffusers</td>
<td>1</td>
<td>38.7</td>
</tr>
<tr>
<td>D</td>
<td>MAF</td>
<td>48 slitted hoses</td>
<td>1</td>
<td>36.5</td>
</tr>
<tr>
<td>E</td>
<td>SAFm</td>
<td>10 modified aerator units each with 3 individual diffusers</td>
<td>1</td>
<td>38.5</td>
</tr>
<tr>
<td>F</td>
<td>SAFm</td>
<td>10 modified aerator units each with 3 individual diffusers</td>
<td>1</td>
<td>36.9</td>
</tr>
<tr>
<td>G</td>
<td>SAFm</td>
<td>10 modified aerator units each with 3 individual diffusers</td>
<td>1</td>
<td>37.7</td>
</tr>
<tr>
<td>H</td>
<td>SAFm2</td>
<td>10 modified aerator units each with 3 individual diffusers</td>
<td>2</td>
<td>77.2</td>
</tr>
<tr>
<td>J</td>
<td>MAF</td>
<td>48 slitted hoses</td>
<td>1</td>
<td>37.2</td>
</tr>
</tbody>
</table>
```

5.7 RESULTS OF FIELD STUDIES

5.7.1 Air Flowrates & Operating Backpressures

Air flowrate data for each test are provided in table C1 in Appendix C. The air flowrate for all tests with one compressor, which shall be referred to as the base air flowrate, averaged 37.6 scfm ± 1.1 scfm. The air flowrate was very steady throughout each test. The air flowrate during test H with 2 compressors operating in parallel was 77.2 scfm, just double that for one compressor.

The air supply backpressure (psig) was 18% higher for operating the MAF aerator at an equivalent air flowrate as the SAF aerator. On average, with one compressor, the MAF aerator (tests A, D, & J) operated at 5.6 psig while the modified SAF aerator (tests E, F, & G) operated at 4.6 psig.

The measurements of the pressure drop across the four diffusers in the corners of the aerator platform gave an average value of 0.217 psi with a range from 0.010–0.551 psi. The results for each individual diffuser are listed in table C2 in Appendix C.
5.7.2 Depth Profiles

In order to determine the extent of mixing in the test tank, column profiles of the DO concentrations and water temperatures at various depths were taken during several aeration tests. The aerator was allowed to run for a given period of time until a significant increase in the surface DO concentration was observed. Then within a five minute time frame, the DO concentrations at various depths down to 8 meters were recorded. Temperature measurements were done likewise during one test. DO measurements were performed using a YSI model 51B DO meter. Temperature measurements were performed using a YSI model 46 TUC 6 channel tele-thermometer with probe.

The results are tabulated in tables C3–C6 in Appendix C. Some data showed a possible slight drop in DO below ~13' depth, but the values were within error of the probe being used. Thus, no significant differences were observed in DO concentrations at the surface versus at any other given depth. Also no differences were observed in temperatures at any given depth. Therefore, based on these data alone, it would have to be concluded that the tank was well mixed.

5.7.3 Effective Tank Volume Mixing

Tank volume data for each test are provided in table C7 in Appendix C. Measuring tank volume is one of the most critical measurements to obtaining a reliable K1A value in each test. Prior to analyzing the fluorescein water samples, it was expected that the values calculated for tank volume for each test would be roughly equivalent—within ±10% of each other. However, the measured tank volumes varied by as much as 50% from each other. This demonstrated that the test tank was not vertically well mixed under all tests. Therefore, measured tank volumes were normalized by dividing by the tank's geometric volume of 10,000 ft³ (figure 15). The normalized value—called the "% effective tank volume"—represents the percentage of the tank being effectively mixed by the aerator in question.

The two lowest recorded effective volumes both occurred when the MAF aerator was operating and the highest effective volume was measured when the SAF5 aerator configuration was employed. The next two largest effective tank volumes were recorded when the SAF10 configuration was used and when the SAFm configuration was operating with 2 compressors (i.e. at double the base air flowrate conditions).

The following table (2) lists visual observations of the water surface area above the aerator during each test configuration:
Figure 15. Effective tank volumes for each field test.
Table 2. Tank Mixing Observations

<table>
<thead>
<tr>
<th>Aerator</th>
<th>Description of the Test Water's Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAF</td>
<td>water &quot;fizzed&quot; to the surface very calmly with only small wave patterns</td>
</tr>
<tr>
<td>SAF₅</td>
<td>water bubbled violently in five distinct fountains ~6&quot; above surface; large waves resulted. Only one fountain per aerator unit was seen and all fountains lined up in a row on the same side of the platform—the side with the highest elevation.</td>
</tr>
<tr>
<td>SAF₁₀</td>
<td>the same observations as for SAF₅ case except 10 distinct fountains were seen and these bubbled at 1/2 the height as the 5 fountains above.</td>
</tr>
<tr>
<td>SAFₙₐₗ</td>
<td>thirty distinct bubbling pools, large waves.</td>
</tr>
</tbody>
</table>

Upon testing the modified aerator units in the field, it was visually apparent that a good air flow distribution system had been found based upon the uniform distribution of 30 bubbling pools across the entire surface area (see figure 16a). The aerator platform could be twisted a foot away from the level position and still good air flow occurred through all 30 diffusers.

The situation was different with the MAF aerator. If the platform did not remain level, a dramatic drop in surface area bubble distribution was observed. Even with the MAF aerator leveled, there was an oval-shaped zone of bubbles above the central area of the platform with dead zones above each of the corner areas (see figure 16b). This indicated that not all of the hose slits were opening up and allowing air through. Even when two compressors were turned on, this same pattern resulted.

5.7.4 BOD

The results of the BOD tests are given in table C8 in Appendix C. The data indicated that no significant BOD was present in the test tank. Therefore, it was not necessary to make corrections for this factor.

5.7.5 $K_{L_A}$ & SAE

It was decided that only data sets which yielded a error estimate ≤ 10% from the residual mean square in calculating the $K_{L_A}$ could be used with any certainty. Therefore no data are shown from tests D and G. Even with this in mind, the data taken during tests A–D showed much higher error than those data taken during tests E–J, 5–9% error vs. 1–3% error, respectively. This was because MAF DO probes were used to record data for the initial tests, A–D, while the SAF DO probe was used for the final tests, E–J. Therefore, much more weight will be placed on the results from the final tests E–J.

The values obtained for $K_{L_A}$, SOTR, and SAE are given in table 3. Note, it is important to keep in mind that three different SAF aerator configurations were tested, SAF₅, SAF₁₀ and SAFₙₐₗ.
Figure 16a. Surface area above MAF aerator operating at an air flow rate of 38 scfm. Notice the dead zones, areas without bubbles, near the corners.

Figure 16b. Surface area above SAF$_m$ aerator operating at an air flowrate of 38 scfm. Notice the uniform bubble distribution across the entire surface.
Table 3. Field Data Summary

<table>
<thead>
<tr>
<th>Test</th>
<th>aerator</th>
<th>probe(s) depth</th>
<th>tank volume</th>
<th>$K_{L/A}$</th>
<th>SOTR</th>
<th>SAE kg O₂ per KwHr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial tests using MAF probes</td>
<td>A</td>
<td>MAF surf. &amp; 10'</td>
<td>4799*</td>
<td>35.1</td>
<td>1.15</td>
<td>1.47</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>SAF₅ 20'</td>
<td>10133</td>
<td>43.0</td>
<td>1.40</td>
<td>2.05</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>SAF₁₀ surface</td>
<td>8492</td>
<td>44.9</td>
<td>1.47</td>
<td>2.30</td>
</tr>
<tr>
<td>final tests using SAF probe</td>
<td>E</td>
<td>SAF₄ 10'</td>
<td>7967</td>
<td>39.5</td>
<td>1.29</td>
<td>1.99</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>SAF₄ 10'</td>
<td>6892</td>
<td>37.4</td>
<td>1.22</td>
<td>2.05</td>
</tr>
<tr>
<td></td>
<td>J</td>
<td>MAF 10'</td>
<td>5154</td>
<td>34.0</td>
<td>1.11</td>
<td>1.72</td>
</tr>
<tr>
<td>2x air flowrate</td>
<td>H</td>
<td>SAF 10'</td>
<td>8641</td>
<td>108</td>
<td>3.53</td>
<td>2.31</td>
</tr>
</tbody>
</table>

All runs are at 37.6 scfm + 1.1 scfm except field test H, which was at 77.2 scfm.

*The tank volume was not measured in MAF test A; so an average value from the other two MAF tests (D &J) was used. Note, test D tank volume data was useful even though its DO data was not.

5.7.6 Initial Tests Compared

In comparing the results of the initial tests, the $K_{L/A}$ for both the SAF₅ and SAF₁₀ aerator configurations were better than for the MAF aerator. The Standard Oxygen Transfer Rate was 22% and 28% higher for the SAF₅ and SAF₁₀ configurations, respectively, when compared to the MAF aerator. This provided a 39% and 56% greater SAE for the SAF aerators, respectively, than the MAF aerator.

5.7.7 Final Tests Compared

The $K_{L/A}$ value was 10–16% higher for the SAF₄ aerator than for the MAF aerator in the final studies. This result, combined with a lower operating pressure, gave the SAF₄ aerator a 16–19% higher Standard Aeration Efficiency as compared to the MAF aerator.

It is important to note that the $K_{L/A}$ value nearly tripled for the SAF₄ aerator when the air flowrate was doubled (SAF₄₂). The SAE jumped an additional 14% over that for the base operating flowrate. Meanwhile, there was no measurable increase in the pressure drop across the orifices in the four sampled diffusers—$\alpha$, $\beta$, $\gamma$, and $\delta$.

It is also important to note that the highest aeration efficiencies occurred when the SAF aerator was operating in the SAF₁₀ and SAF₄₂ configurations.
5.8 DISCUSSION OF FIELD STUDY

The SAF aerator showed superior performance to the MAF aerator in several key areas: a) operating backpressure, b) plan area design, c) effective mixing, d) oxygen transfer rate, and e) aeration efficiency.

5.8.1 Operating Backpressure

Because the pressure drop across the orifices is virtually negligible (0.22 psi on the average), the SAF aerator under all configurations studied—SAF₁₀, SAF₅, SAFₐ—operated at backpressures only slightly higher than the hydrostatic pressure at the same depth as the orifices. When the airflow was well distributed, the SAFₐ aerator operated at lower backpressures than the MAF aerator. These results translate into a cost savings for operating blowers or compressors when operating the SAF aerator versus the MAF aerator.

If the aerator were operating at peak efficiency, one would have expected the operating backpressure to quadruple when the airflow rate was doubled. Since it did not, but only increased slightly, it indicated the SAFₐ aerator was overdesigned for the base operating airflow rate used in this investigation. What is theorized to be occurring is the following: at the base operating airflow rate (38 scfm) only the upper few rows of orifices have airflow going through them. As the airflow increases more holes become active with the airflow per hole remaining essentially constant.

What this suggests is even though the SAF aerator performed better than the MAF aerator, and at a lower operating costs, there is still room for optimizing the efficiency of the SAF design by merely testing it at higher airflow rates until the optimum is determined. This means that the SAF aerator platform can be used with less aerator units, if the same oxygen transfer rate as the MAF aerator were desired. In other words, the SAF aerator with 10 aerator units could be operated in the place of several MAF aerator platforms.

Basically, the SAF diffuser design allows for greater flexibility and control to meet MAF's varying aeration needs because the number of open orifices will change as the airflow rate is adjusted. It can be operated at high airflow rates when necessary, such as in late summer when the DO concentration is low. In this case most of the orifices would have airflow passing through them. Or at other times of the year when less oxygen transfer is required, the airflow rate could be decreased. As the pressure inside the plenum decreased due to lowering the airflow rate, the water level would rise, thereby plugging rows of orifices from the bottom row up until the hydrostatic pressure was counterbalanced by the lowered air pressure. Even though the diffusers would be operating at a less than optimal flowrate, they would still maintain good aeration efficiencies as has been shown in these studies.

Because of its design, the MAF aerator requires a minimum backpressure before the hose slits will open. In the case of the SAF design there is virtually no cost associated with keeping orifices open. The only pumping cost involved is overcoming the hydrostatic pressure at the depth the aerator is located and the slight headloss associated with the flow restrictors designed to evenly distribute airflow to each diffuser unit.
5.8.2 Design Layout

The SAF diffuser allows for greater flexibility in designing aerator layouts. Since each aerator unit can act as a stand alone device—indeed, each diffuser could stand alone as well—the number of configurations of these type of air distribution systems is manifold. For example, it should be noted that the 8' x 20' aerator platform used in this field study had room to house a minimum of twenty 8' long aerator units. Since Minnesota Aquafarms desired to utilize a row of pumps to circulate lake water over the surface of the aerator platforms, this latter configuration would minimize the cross-sectional width area required to be circulated. For example, one SAF aerator platform operating at a higher air flowrate could be used to replace several MAF platforms operating at the present flow rate. This would eliminate the need for several platforms that would be spread out over a wider cross-sectional area, and thus requiring more pumping energy to circulate this larger volume of water across the platforms.

Each SAF diffuser unit could be manufactured separately as well. At present, Minnesota Aquafarms cannot place their present aerator platform directly within the fish pens, but rather outside the pens because the fish get caught between the hoses and the aerator bubbles disturb the fish. With the SAF design, individual diffusers could be placed around a given pen perimeter instead of using one large platform off to one side of the pen. This would allow a more effective oxygen distribution to all areas of the pen. A few individual diffusers could also be strategically placed within a pen. As individual diffusers, the potential harm to the fish would be minimized.

5.8.3 Effective Mixing

As demonstrated by the results of the fluorescein tests, the effective tank volume greatly decreased when operating the MAF aerator as opposed to the SAF design. Greater vertical mixing occurred when operating the SAF aerator in any configuration.

It is even more interesting to note that the effective tank volume increased under SAF configurations when the air flow rate/diffuser was increased. For example, in the SAF5 configuration, five bubbling fountains were observed at the water surface. Although each plenum was open for air flow to distribute to six diffusers, only one diffuser in each plenum had air flow moving through it. When compared to the SAFm configuration operating with 30 diffusers, the air flow rate/diffuser was six times higher for the SAF5 design than for the SAFm design. Since the SAF diffuser operates on the principle of induced water velocity in a vertical draft tube, when a diffuser's air flowrate increases, greater vertical mixing occurs due to the increased vertical water velocity moving through the tube.

Referring back to figure 15, if the effective tank volumes for the various SAF configurations are compared on the basis of air flowrate per diffuser, then as the air flowrate per diffuser increases so does the effective tank volume. Using the air flowrate per diffuser for the SAFm design as a baseline, the SAFm2, SAF10, and SAF5 configurations had 2, 3 and 6 times the air flowrate per diffuser, respectively.

In terms of plan area bubble distribution, the SAFm aerator outperformed the MAF aerator. Dead zones were readily apparent at the corners of the MAF plan area, which were not observed for the SAFm design. The poor surface area bubble distribution in the MAF
aerator most likely contributed to the poor water mixing and low effective tank volumes found with the MAF design.

A contributing factor to poor bubble area distribution in the MAF design is this aerator's sensitivity to changes in bubble area distribution when the aerator frame is not level by even a few inches. When the platform is not level the bubble plan area decreases. Once the SAF aerator was modified to the SAF_m configuration, the platform could be raised and lowered several time without any severe changes in bubble area distribution. At Minnesota Aquafarms, all equipment, including aerators, are suspended from floating docks due to the depth of the lake. Thus, the SAF_m design would be desired over the MAF design in this setting where maintaining leveled aerator platforms is a relatively difficult task.

5.8.4 Oxygen Transfer Rate & Aeration Efficiency

The oxygen transfer rate as demonstrated by the $K_{LA}$ and SOTR values in the final studies, demonstrated that even under sub-optimal air flowrates the SAF_m design outperformed the MAF design. Coupled with the decreased operating backpressures required for the SAF_m design, this translates in turn into a significantly higher aeration efficiency. As a result lower operating costs will be incurred by the client.

Based upon the final tests, an estimate of the costs savings for operating the SAF aerator versus the MAF aerator was performed. Assume $X$ number of kilograms of oxygen needs to be transferred to a given volume of lake water. Dividing $X$ by SAE gives the number of kilowatt hours of energy required to input that mass of oxygen into the water. For example, to input 10 kg of oxygen into the lake, the energy costs associated with operating the MAF, SAF_m, and SAF_m2 aerator designs would be 5.81, 4.95 and 4.33 kilowatt hours, respectively. Regardless of the amount of oxygen that needs to be transferred, operating the SAF aerator in place of the MAF aerator results in a 14.8% to 25.5% cost savings (with the SAF_m and SAF_m2 operating air flowrates, respectively). Even greater cost savings could be achieved if optimization of the air flowrate was performed.

5.8.5 Plugging

Another advantage of the SAF diffuser, is that given the orifice size, this diffuser will not readily plug like other conventional diffusers, such as porous stone diffusers. This means that the air supply can come from compressors, as demonstrated here, which normally are a bane in aeration devices due to orifice clogging from oil in the compressor air lines. Since this diffuser may be operated using either blowers or compressors, the client user is afforded greater flexibility in operation.

The MAF design is not very susceptible to clogging as well. However, the MAF aerator is dependent upon the hose slits remaining almost shut in order to produce near optimum sized bubbles. If operating pressures are too high, the plastic slits will permanently deform and remain in the open position. This will have a detrimental effect on the aeration efficiency when the pressure is decreased back to normal levels. Eventually even if normal backpressures are maintained the hose slits will deform and efficiency will drop until the hoses are replaced.
VI. CONCLUSIONS

The SAF Aerator of rectangular planform is a viable alternative to the present aeration design employed at Minnesota Aquafarms. It has the advantages of allowing flexibility and control over the plan-area layout and air flow rates required under varying DO concentration needs. It is simple and inexpensive to manufacture with all materials commercially available. It operated at a lower backpressure, and yielded a higher oxygen transfer rate as well as a better aeration efficiency than Minnesota Aquafarms present aeration system. A minimum energy cost savings of 25.5% can be expected by using the prototype SAF aerator developed in this study in place of the MAF aerator. It was also found that even greater cost savings could by realized by optimizing the design further. The SAF aerator is a viable replacement for the aerator employed by Minnesota Aquafarms and should be given serious consideration in aquafarm applications.
REFERENCES


Rieth, M.—personal communication, January 1995. Mr. Rieth is employed at the Metropolitan Waste Control Commission, St. Paul, MN.


APPENDICES

APPENDIX A:  Equipment and Chemicals

APPENDIX B:  Data from Lab Studies

APPENDIX C:  Data from Field Studies
APPENDIX A
EQUIPMENT AND CHEMICALS

EQUIPMENT FOR LAB STUDIES

Aquarium heaters—300 watt, Visitherm model VTH300, Aquarium Systems, 8141 Tyler Blvd, Mentor, OH.

Barometer—Springfield Weather station model, Woodridge, NJ. calibrated against a model 5EB1183 mercury barometer from Precision Thermometer & Instrument Co., Philadelphia.

Datalogger & storage module—model CR10, Campbell Scientific Inc., Logan, UT.

Dissolved oxygen meter—YSI, Inc. model 58 with model 5739 DO probe, Yellow Springs, OH. The DO probe was calibrated according to the manufacturer's instructions by measuring the barometric pressure and setting the DO % saturation accordingly. Probe membranes were replaced every two weeks using a YSI, Inc. membrane—KCl kit, cat. # 5775.

Oil filter—Norgren oil removal (coalescing) compressed air filter, model F60, max. up to 150 psig & 125° F.

Pressure gauge—digital scale 0–29.9″ Hg with an accuracy of +2% of reading, TIF Instruments, Inc. model 9675, Miami, FL.

Pressure regulator—a Schrader No. 3571-3200 regulator, max. inlet pressure 300 psig, range 5–250 psig, from Scovill Fluid Power Div., Wake Forest, NC.

Pump—portable utility pump, 1/2 HP, 8 amps, 1290 GPH at 15 ft lift.

Rotameter—scale reading 0–2.2 cfm, model 1114CJ31CLHAA, Brooks Instrument Division, Emerson Electric Co. Hatfield, PA. The following formula was used to correct scale readings to scfm: scfm = (scale reading) * A * B where A = sq root [(P +14.7)/14.7] and B = sq root [530/(T + 460)]. This formula was supplied by Mr. Howard Kramer of Brooks Instrument Division.

SAFHL air compressor—used as the air supply for all lab studies.

SAFHL tap water—from the municipal drinking water supply. This was used as the water source for all lab tests.

Temperature probes and meter—YSI, Inc. model 46 TUC Tele-thermometer (6 channel), Yellow Springs, OH. The temperature probes were calibrated against a Fisherbrand® model 15–000A mercury thermometer 0–50.0° C with graduations of 0.1 °C.
Water & particle filter—Norgren general purpose compressed air filter, model max. up to 150 psig & 120°F.

Weighing balance—Ohaus triple beam balance 0–2610 g range with 0.1 g increments used to weigh cobalt chloride & sodium sulfite.

CHEMICALS FOR LAB STUDIES

Cobalt Chloride•6H₂O—CoCl₂•6H₂O, M.W 237.93, A.C.S. grade, Mallinckrodt cat. # 4532, lot 4532KDNT.

Cobalt Chloride•6H₂O—CoCl₂•6H₂O, M.W 237.93, Spectrum Chemical Co., Redondo Beach, CA, cat. # C1850, lot 10030D51.

Sodium Sulfite—NaSO₃, M.W. 126.05, A.C.S. grade, Allied Chemical, NY, NY, lot W011.

Sodium Sulfite—NaSO₃, M.W. 126.05, A.C.S. grade, EM Science, Gibbstown, NJ. cat. # SX0785-3, lot 32122233.

EQUIPMENT FOR FIELD STUDIES

Air Compressors—Gardner-Denver model EJBODB, rotary screw type, provided by Minnesota Aquafarms, Inc.

DO probes—manufactured by Ziegler Brothers, Gardens, PA, and provided by Minnesota Aquafarms, Inc.

Orifice plate—manufactured at SAFHL, 1.000" diameter orifice with a pipe diameter of 2.036". Air flowrate was calculated based on gauge pressure & temperature upstream of the orifice and the differential pressure across the orifice according to guidelines in Bean, 1971.

Pressure transducers—0–1 psi differential, Sensym model scx01dn; and 0–15 psi differential, Sensym model scx15dn.

Temperature probes—manufactured by Ziegler Brothers, Gardens, PA, and provided by Minnesota Aquafarms, Inc.

Weighing balance—Mettler H72 single pan balance, capacity 100 g ± 0.0001 g used to weigh fluorescein.

The following items listed in the lab study above were also used in the field study: the DO probe & meter, temperature probes & meter, data logger & storage module, and barometer.

CHEMICALS FOR FIELD STUDIES

Fluorescein—C₂₀H₁₂O₅, M.W. 332.31, Janssen Chimica cat. # 11.924.90, lot 18377/1.
EQUIPMENT FOR DATA ANALYSIS

ASCE 87 Software Program: "Non-linear Estimation of Unsteady State Oxygen Transfer". This program takes DO concentration versus time data obtained from experiments and uses a non-linear regression routine to fit an equation to the data curve. The program provides a least squares estimate of the parameters $K_L$, $C_s$ and $C_0$. This program is provided with the manual: ASCE Standard "Measurement of Oxygen Transfer in Clean Water," American Society of Civil Engineers, NY, NY. July 1984.

Fluorometer, Turner series 10, utilizing 13 x 100 mm borosilicate glass tubes.

IBM compatible 286 & 486 computers and available printers.
### APPENDIX B
DATA FROM LAB STUDIES

Table B1. Results of lab tests performed on the rectangular prototype diffusers.

<table>
<thead>
<tr>
<th>date</th>
<th>run</th>
<th>tube height L2</th>
<th>tube width D0</th>
<th>mouth width D0m</th>
<th>rows of orifice holes</th>
<th>K_La</th>
<th>Average K_La</th>
<th>K_LA</th>
</tr>
</thead>
<tbody>
<tr>
<td>25-Jan</td>
<td>a</td>
<td>7 inches</td>
<td>5 inches</td>
<td>2 inches</td>
<td>12</td>
<td>0.0291</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25-Jan</td>
<td>b</td>
<td>7 inches</td>
<td>5 inches</td>
<td>2 inches</td>
<td>12</td>
<td>0.0292</td>
<td>0.0292</td>
<td>827</td>
</tr>
<tr>
<td>27-Jan</td>
<td>a</td>
<td>5 inches</td>
<td>5 inches</td>
<td>2 inches</td>
<td>12</td>
<td>0.0287</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27-Jan</td>
<td>b</td>
<td>5 inches</td>
<td>5 inches</td>
<td>2 inches</td>
<td>12</td>
<td>0.0293</td>
<td>0.0290</td>
<td>822</td>
</tr>
<tr>
<td>28-Jan</td>
<td>a</td>
<td>4 inches</td>
<td>5 inches</td>
<td>2 inches</td>
<td>12</td>
<td>0.0273</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28-Jan</td>
<td>b</td>
<td>4 inches</td>
<td>5 inches</td>
<td>2 inches</td>
<td>12</td>
<td>0.0285</td>
<td>0.0279</td>
<td>791</td>
</tr>
<tr>
<td>31-Jan</td>
<td>a</td>
<td>3 inches</td>
<td>5 inches</td>
<td>2 inches</td>
<td>12</td>
<td>0.0279</td>
<td></td>
<td></td>
</tr>
<tr>
<td>31-Jan</td>
<td>b</td>
<td>3 inches</td>
<td>5 inches</td>
<td>2 inches</td>
<td>12</td>
<td>0.0275</td>
<td>0.0277</td>
<td>785</td>
</tr>
<tr>
<td>2-Feb</td>
<td>a</td>
<td>2 inches</td>
<td>5 inches</td>
<td>2 inches</td>
<td>12</td>
<td>0.0259</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-Feb</td>
<td>b</td>
<td>2 inches</td>
<td>5 inches</td>
<td>2 inches</td>
<td>12</td>
<td>0.0254</td>
<td>0.0257</td>
<td>728</td>
</tr>
<tr>
<td>3-Feb</td>
<td>a</td>
<td>0 inches</td>
<td>5 inches</td>
<td>2 inches</td>
<td>12</td>
<td>0.0237</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4-Feb</td>
<td>b</td>
<td>0 inches</td>
<td>5 inches</td>
<td>2 inches</td>
<td>12</td>
<td>0.0239</td>
<td>0.0238</td>
<td>674</td>
</tr>
<tr>
<td>8-Feb</td>
<td>a</td>
<td>7 inches</td>
<td>2.5 inches</td>
<td>1 inches</td>
<td>12</td>
<td>0.0285</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8-Feb</td>
<td>b</td>
<td>7 inches</td>
<td>2.5 inches</td>
<td>1 inches</td>
<td>12</td>
<td>0.0285</td>
<td>0.0285</td>
<td>808</td>
</tr>
<tr>
<td>9-Feb</td>
<td>a</td>
<td>5 inches</td>
<td>2.5 inches</td>
<td>1 inches</td>
<td>12</td>
<td>0.0281</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9-Feb</td>
<td>b</td>
<td>5 inches</td>
<td>2.5 inches</td>
<td>1 inches</td>
<td>12</td>
<td>0.0284</td>
<td>0.0283</td>
<td>802</td>
</tr>
<tr>
<td>10-Feb</td>
<td>a</td>
<td>4 inches</td>
<td>2.5 inches</td>
<td>1 inches</td>
<td>12</td>
<td>0.0274</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13-Feb</td>
<td>a</td>
<td>4 inches</td>
<td>2.5 inches</td>
<td>1 inches</td>
<td>12</td>
<td>0.0282</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13-Feb</td>
<td>b</td>
<td>4 inches</td>
<td>2.5 inches</td>
<td>1 inches</td>
<td>12</td>
<td>0.0283</td>
<td>0.0280</td>
<td>793</td>
</tr>
<tr>
<td>14-Feb</td>
<td>a</td>
<td>3 inches</td>
<td>2.5 inches</td>
<td>1 inches</td>
<td>12</td>
<td>0.0274</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14-Feb</td>
<td>b</td>
<td>3 inches</td>
<td>2.5 inches</td>
<td>1 inches</td>
<td>12</td>
<td>0.0276</td>
<td>0.0275</td>
<td>779</td>
</tr>
<tr>
<td>18-Feb</td>
<td>a</td>
<td>7 inches</td>
<td>4 inches</td>
<td>1 inches</td>
<td>12</td>
<td>0.0301</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18-Feb</td>
<td>b</td>
<td>7 inches</td>
<td>4 inches</td>
<td>1 inches</td>
<td>12</td>
<td>0.0297</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21-Feb</td>
<td>b</td>
<td>7 inches</td>
<td>4 inches</td>
<td>1 inches</td>
<td>12</td>
<td>0.0305</td>
<td>0.0301</td>
<td>853</td>
</tr>
<tr>
<td>23-Feb</td>
<td>a</td>
<td>5 inches</td>
<td>4 inches</td>
<td>1 inches</td>
<td>12</td>
<td>0.0291</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24-Feb</td>
<td>b</td>
<td>5 inches</td>
<td>4 inches</td>
<td>1 inches</td>
<td>12</td>
<td>0.0293</td>
<td>0.0292</td>
<td>827</td>
</tr>
<tr>
<td>16-Mar</td>
<td>a</td>
<td>7 inches</td>
<td>3.5 inches</td>
<td>0.5 inches</td>
<td>12</td>
<td>0.0301</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16-Mar</td>
<td>b</td>
<td>7 inches</td>
<td>3.5 inches</td>
<td>0.5 inches</td>
<td>12</td>
<td>0.0306</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16-Mar</td>
<td>c</td>
<td>7 inches</td>
<td>3.5 inches</td>
<td>0.5 inches</td>
<td>12</td>
<td>0.0314</td>
<td>0.0307</td>
<td>870</td>
</tr>
<tr>
<td>22-Mar</td>
<td>b</td>
<td>7 inches</td>
<td>3.5 inches</td>
<td>0.5 inches</td>
<td>8</td>
<td>0.0313</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23-Mar</td>
<td>a</td>
<td>7 inches</td>
<td>3.5 inches</td>
<td>0.5 inches</td>
<td>8</td>
<td>0.0314</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23-Mar</td>
<td>b</td>
<td>7 inches</td>
<td>3.5 inches</td>
<td>0.5 inches</td>
<td>8</td>
<td>0.0324</td>
<td>0.0317</td>
<td>898</td>
</tr>
<tr>
<td>5-Apr</td>
<td>a</td>
<td>7 inches</td>
<td>3.5 inches</td>
<td>0.5 inches</td>
<td>4</td>
<td>0.0311</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-Apr</td>
<td>b</td>
<td>7 inches</td>
<td>3.5 inches</td>
<td>0.5 inches</td>
<td>4</td>
<td>0.0309</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6-Apr</td>
<td>a</td>
<td>7 inches</td>
<td>3.5 inches</td>
<td>0.5 inches</td>
<td>4</td>
<td>0.0305</td>
<td>0.0308</td>
<td>873</td>
</tr>
</tbody>
</table>
APPENDIX C
DATA FROM FIELD STUDIES

AIR FLOWRATE DATA

Table C1. Air Flowrates For Field Studies

<table>
<thead>
<tr>
<th>test-aerator</th>
<th>Air Supply Pressure* (average)</th>
<th>Pressure Drop Across Orifice (average)</th>
<th>Air Line Temp.</th>
<th>Calculated Air Flow Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>psig</td>
<td>% CV</td>
<td>psig</td>
<td>% CV</td>
</tr>
<tr>
<td>Test A-MAF</td>
<td>6.43</td>
<td>0.8%</td>
<td>0.182</td>
<td>1.2%</td>
</tr>
<tr>
<td>Test B-SAF₁₅</td>
<td>5.32</td>
<td>0.9%</td>
<td>0.205</td>
<td>3.5%</td>
</tr>
<tr>
<td>Test C-SAF₁₀</td>
<td>4.74</td>
<td>0.1%</td>
<td>0.214</td>
<td>6.1%</td>
</tr>
<tr>
<td>Test D-MAF</td>
<td>5.90</td>
<td>6.0%</td>
<td>0.183</td>
<td>3.4%</td>
</tr>
<tr>
<td>Test E-SAF₉₉</td>
<td>4.86</td>
<td>0.7%</td>
<td>0.209</td>
<td>1.7%</td>
</tr>
<tr>
<td>Test F-SAF₉₉</td>
<td>4.59</td>
<td>0.2%</td>
<td>0.198</td>
<td>2.7%</td>
</tr>
<tr>
<td>Test G-SAF₉₉</td>
<td>4.84</td>
<td>0.3%</td>
<td>0.204</td>
<td>0.8%</td>
</tr>
<tr>
<td>Test H-SAF₉₂</td>
<td>6.57</td>
<td>2.2%</td>
<td>0.819</td>
<td>1.4%</td>
</tr>
<tr>
<td>Test J-MAF</td>
<td>5.06</td>
<td>1.4%</td>
<td>0.200</td>
<td>1.0%</td>
</tr>
</tbody>
</table>

* Measured upstream of orifice plate
# air flow with two compressors operating in parallel.

PRESSURE DROP ACROSS DIFFUSER ORIFICES

Table C2. Summary of pressure drops across orifices for SAF diffusers

<table>
<thead>
<tr>
<th>Test</th>
<th>α₁</th>
<th>α₂</th>
<th>β₁</th>
<th>β₂</th>
<th>γ₁</th>
<th>γ₂</th>
<th>δ₁</th>
<th>δ₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>0.166</td>
<td>0.186</td>
<td>0.411</td>
<td>0.352</td>
<td>0.387</td>
<td>0.201</td>
<td>0.364</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>0.056</td>
<td>0.053</td>
<td>0.408</td>
<td>0.443</td>
<td>0.015</td>
<td>0.010</td>
<td>0.047</td>
<td>0.067</td>
</tr>
<tr>
<td>G</td>
<td>0.089</td>
<td>0.085</td>
<td>0.507</td>
<td>0.551</td>
<td>0.111</td>
<td>0.109</td>
<td>0.007</td>
<td>0.025</td>
</tr>
<tr>
<td>H*</td>
<td>0.013</td>
<td>0.013</td>
<td>0.508</td>
<td>0.505</td>
<td>0.382</td>
<td>0.382</td>
<td>0.146</td>
<td>0.124</td>
</tr>
</tbody>
</table>

Summary of Tests E, F, G, & H
- lowest value 0.010
- highest value 0.551
- average value 0.216

*For test H two compressors were operating with double the air flow rate of one compressor.
TABLES C3–C6. DEPTH PROFILES

Table C3. DO Depth Profile during Field Test A

<table>
<thead>
<tr>
<th>Depth (meters (ft))</th>
<th>DO, mg/L after 25 min*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>13.4</td>
</tr>
<tr>
<td>3 (9.8)</td>
<td>13.4</td>
</tr>
<tr>
<td>4 (13.1)</td>
<td>13.1</td>
</tr>
<tr>
<td>5 (16.4)</td>
<td>13.0</td>
</tr>
<tr>
<td>6 (19.7)</td>
<td>13.1</td>
</tr>
<tr>
<td>7 (23)</td>
<td>13.5</td>
</tr>
</tbody>
</table>

*Time after start of aeration

Table C4. DO & Temperature Depth Profiles during Field Test B

<table>
<thead>
<tr>
<th>Depth (meters (ft))</th>
<th>Temperature °C after 95 min*</th>
<th>DO, mg/L after 95 min*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>3.6</td>
<td>12.2</td>
</tr>
<tr>
<td>2 (6.6)</td>
<td>3.6</td>
<td>12.2</td>
</tr>
<tr>
<td>4 (13.1)</td>
<td>3.6</td>
<td>12.2</td>
</tr>
<tr>
<td>6 (19.7)</td>
<td>3.6</td>
<td>11.6</td>
</tr>
<tr>
<td>8 (26.2)</td>
<td>3.6</td>
<td>11.9</td>
</tr>
</tbody>
</table>

*Time after start of aeration

Table C5. DO Depth Profiles during Field Test C

<table>
<thead>
<tr>
<th>Depth (meters (ft))</th>
<th>DO, mg/L after 15 min*</th>
<th>DO, mg/L after 60 min*</th>
<th>DO, mg/L after 165 min*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>11.4</td>
<td>12.4</td>
<td>13.6</td>
</tr>
<tr>
<td>1 (3.3)</td>
<td>11.4</td>
<td>12.4</td>
<td>13.6</td>
</tr>
<tr>
<td>2 (6.6)</td>
<td>11.4</td>
<td>12.4</td>
<td>13.6</td>
</tr>
<tr>
<td>3 (9.8)</td>
<td>11.4</td>
<td>12.6</td>
<td>13.6</td>
</tr>
<tr>
<td>4 (13.1)</td>
<td>11.4</td>
<td>12.6</td>
<td>13.4</td>
</tr>
<tr>
<td>5 (16.4)</td>
<td>11.4</td>
<td>12.6</td>
<td>13.4</td>
</tr>
<tr>
<td>6 (19.7)</td>
<td>11.4</td>
<td>12.5</td>
<td>13.4</td>
</tr>
<tr>
<td>7 (23.0)</td>
<td>11.4</td>
<td>12.5</td>
<td>13.4</td>
</tr>
<tr>
<td>8 (26.2)</td>
<td>11.4</td>
<td>12.6</td>
<td>13.4</td>
</tr>
<tr>
<td>9 (29.5)</td>
<td></td>
<td>12.6</td>
<td></td>
</tr>
<tr>
<td>9.5 (31.2)</td>
<td></td>
<td>12.4</td>
<td></td>
</tr>
</tbody>
</table>

*Time after start of aeration
Table C6. DO Depth Profiles during Field Test E.

<table>
<thead>
<tr>
<th>depth (meters)</th>
<th>DO, mg/L after 13 min*</th>
<th>DO, mg/L after 58 min*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.65</td>
<td>12.40</td>
</tr>
<tr>
<td>2</td>
<td>11.70</td>
<td>12.60</td>
</tr>
<tr>
<td>3</td>
<td>11.65</td>
<td>12.50</td>
</tr>
<tr>
<td>4</td>
<td>11.65</td>
<td>12.60</td>
</tr>
<tr>
<td>5</td>
<td>11.60</td>
<td>12.50</td>
</tr>
<tr>
<td>6</td>
<td>11.60</td>
<td>12.80</td>
</tr>
<tr>
<td>7</td>
<td>11.40</td>
<td>12.80</td>
</tr>
<tr>
<td>8</td>
<td>11.40</td>
<td>12.80</td>
</tr>
</tbody>
</table>

*Time after start of aeration

EFFECTIVE TANK VOLUME DATA

Table C7. Effective Tank Volumes from Fluorescein Tests

<table>
<thead>
<tr>
<th>Field Test</th>
<th>Aerator Tested</th>
<th>Tank Volume</th>
<th>% Effective Tank Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>MAF</td>
<td>not measured</td>
<td>101%</td>
</tr>
<tr>
<td>B</td>
<td>SAF5</td>
<td>10133</td>
<td>84.9%</td>
</tr>
<tr>
<td>C</td>
<td>SAF10</td>
<td>8492</td>
<td>84.9%</td>
</tr>
<tr>
<td>D</td>
<td>MAF</td>
<td>5154</td>
<td>51.5%</td>
</tr>
<tr>
<td>E</td>
<td>SAFm</td>
<td>7967</td>
<td>79.7%</td>
</tr>
<tr>
<td>F</td>
<td>SAFm</td>
<td>6892</td>
<td>68.9%</td>
</tr>
<tr>
<td>G</td>
<td>SAFm</td>
<td>6892</td>
<td>68.9%</td>
</tr>
<tr>
<td>H</td>
<td>SAFm2</td>
<td>8641</td>
<td>86.4%</td>
</tr>
<tr>
<td>J</td>
<td>MAF</td>
<td>4444</td>
<td>44.4%</td>
</tr>
</tbody>
</table>

% Effective tank volume is based on a geometric tank volume of 10,000 ft³

BOD DATA

Table C8. BOD Test Results

<table>
<thead>
<tr>
<th>date</th>
<th>time</th>
<th>DO Conc. mg/L</th>
<th>period hours</th>
<th>Change in DO mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-May-95</td>
<td>6:20 PM</td>
<td>11.09</td>
<td>4</td>
<td>-0.08</td>
</tr>
<tr>
<td>5-May-95</td>
<td>10:10 PM</td>
<td>11.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-May-95</td>
<td>11:00 PM</td>
<td>10.22</td>
<td>11</td>
<td>-0.08</td>
</tr>
<tr>
<td>6-May-95</td>
<td>10:15 AM</td>
<td>10.14</td>
<td>25</td>
<td>-0.03</td>
</tr>
<tr>
<td>7-May-95</td>
<td>11:15 AM</td>
<td>10.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7-May-95</td>
<td>11:15 AM</td>
<td>10.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8-May-95</td>
<td>7:05 AM</td>
<td>10.06</td>
<td>20</td>
<td>-0.08</td>
</tr>
</tbody>
</table>
Table C9. Data Summary of Oxygen Transfer Rates and Aeration Efficiencies For Field Tests.

<table>
<thead>
<tr>
<th>Field Test</th>
<th>aerator depth</th>
<th>K_La error*</th>
<th>water temp</th>
<th>K_La20</th>
<th>tank volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>MAF</td>
<td>0.0104</td>
<td>6.0%</td>
<td>3.9</td>
<td>0.0152</td>
</tr>
<tr>
<td>A</td>
<td>MAF</td>
<td>0.0107</td>
<td>7.0%</td>
<td>3.9</td>
<td>0.0157</td>
</tr>
<tr>
<td>avg A</td>
<td>MAF</td>
<td>0.0106</td>
<td></td>
<td>3.9</td>
<td>0.0155</td>
</tr>
<tr>
<td>B</td>
<td>SAF</td>
<td>0.0061</td>
<td>9.0%</td>
<td>3.6</td>
<td>0.0090</td>
</tr>
<tr>
<td>C</td>
<td>SAF_10</td>
<td>0.0076</td>
<td>5.0%</td>
<td>3.6</td>
<td>0.0112</td>
</tr>
<tr>
<td>E</td>
<td>SAF_m</td>
<td>0.0073</td>
<td>2.0%</td>
<td>4.5</td>
<td>0.0105</td>
</tr>
<tr>
<td>F</td>
<td>SAF_m</td>
<td>0.0079</td>
<td>2.0%</td>
<td>4.3</td>
<td>0.0115</td>
</tr>
<tr>
<td>H</td>
<td>SAF_m2</td>
<td>0.0181</td>
<td>3.0%</td>
<td>4.1</td>
<td>0.0264</td>
</tr>
<tr>
<td>J</td>
<td>MAF</td>
<td>0.0096</td>
<td>1.0%</td>
<td>4.1</td>
<td>0.0140</td>
</tr>
</tbody>
</table>

Table C9. Data Summary of Oxygen Transfer Rates and Aeration Efficiencies For Field Tests.

<table>
<thead>
<tr>
<th>Field Test</th>
<th>aerator depth</th>
<th>K_La</th>
<th>SOTR</th>
<th>Q_{st-air} flowrate</th>
<th>w-mass flowrate</th>
<th>P_2</th>
<th>power input</th>
<th>SAE</th>
</tr>
</thead>
<tbody>
<tr>
<td>avg A</td>
<td>MAF</td>
<td>35.1</td>
<td>1.15</td>
<td>36.9</td>
<td>0.0212</td>
<td>20.95</td>
<td>781</td>
<td>1.47</td>
</tr>
<tr>
<td>B</td>
<td>SAF</td>
<td>43.0</td>
<td>1.40</td>
<td>38.0</td>
<td>0.0219</td>
<td>19.82</td>
<td>686</td>
<td>2.05</td>
</tr>
<tr>
<td>C</td>
<td>SAF_10</td>
<td>44.9</td>
<td>1.47</td>
<td>38.7</td>
<td>0.0223</td>
<td>19.23</td>
<td>638</td>
<td>2.30</td>
</tr>
<tr>
<td>E</td>
<td>SAF_m</td>
<td>39.5</td>
<td>1.29</td>
<td>38.5</td>
<td>0.0222</td>
<td>19.35</td>
<td>648</td>
<td>1.99</td>
</tr>
<tr>
<td>F</td>
<td>SAF_m</td>
<td>37.4</td>
<td>1.22</td>
<td>36.9</td>
<td>0.0212</td>
<td>19.09</td>
<td>596</td>
<td>2.05</td>
</tr>
<tr>
<td>H</td>
<td>SAF_m2</td>
<td>108.0</td>
<td>3.53</td>
<td>77.2</td>
<td>0.0445</td>
<td>20.45</td>
<td>1527</td>
<td>2.31</td>
</tr>
<tr>
<td>J</td>
<td>MAF</td>
<td>34.0</td>
<td>1.11</td>
<td>37.2</td>
<td>0.0214</td>
<td>19.56</td>
<td>646</td>
<td>1.72</td>
</tr>
</tbody>
</table>

* error estimate from residual mean square. Test results from any probe over 10% error were not used in this analysis.

# Tank volume was not measured in test A; the average value from all the other two MAF tests (D & J) combined was used (see table C7).

In calculating power input, the air temperature inside the compressor house was not measured, but estimated at 300 K for all tests.

All runs are with 1 compressor except field test H, which was with 2 compressors.