THE EVALUATION OF CHEMICAL REACTION DYNAMICS WITHIN SWINE-RAISING FACILITY UNDERDRAINS: IMPLICATIONS TO ODOR EVOLUTION AND ASSESSMENT OF ABATEMENT STRATEGIES

By

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This research investigated the chemodynamics of the underdrains found at swine-raising facilities. The maintenance of aerobic conditions and introduction of aerobic bacteria to expedite the treatment process and control odor formation were investigated. A pilot-scale system that mimicked an industrial swine-raising facility was used in this study. Aeration and aeration with bacterial seed additions were evaluated against a standard pit recharge system, which served as the control. The effectiveness was measured using water quality testing, odor assessments by a human sensory panel, and air phase measurements of hydrogen sulfide and ammonia. The results indicated that both aeration and aeration with seeding under low loading conditions were effective in reducing BOD, COD, volatile acids, and phenol concentration as well as overall odor intensity as compared to the control;
however, neither was effective in reducing the ammonia, phosphate, or total solids concentrations. At mid and high loadings, little benefit was observed.
DEDICATION

I would like to dedicate this research to Dr. Joseph L. Ferguson, Jr. for his support and encouragement throughout the completion of this thesis.
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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEDICATION</td>
<td>ii</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>x</td>
</tr>
<tr>
<td>CHAPTER</td>
<td></td>
</tr>
<tr>
<td>I. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>Problem Statement</td>
<td>1</td>
</tr>
<tr>
<td>II. LITERATURE REVIEW</td>
<td>9</td>
</tr>
<tr>
<td>Introduction</td>
<td>9</td>
</tr>
<tr>
<td>Anaerobic Lagoons-Current Practice</td>
<td>10</td>
</tr>
<tr>
<td>Odor Formation In Anaerobic Lagoons</td>
<td>11</td>
</tr>
<tr>
<td>Key Anaerobic Reactions</td>
<td>12</td>
</tr>
<tr>
<td>Acid-Forming Bacteria</td>
<td>14</td>
</tr>
<tr>
<td>Hydrogen-Producing Acetogenic Bacteria</td>
<td>14</td>
</tr>
<tr>
<td>Acetoclastic Methanogens</td>
<td>15</td>
</tr>
<tr>
<td>Carbon Dioxide-Reducing Methanogens</td>
<td>15</td>
</tr>
<tr>
<td><em>Sulfuromonas</em></td>
<td>16</td>
</tr>
<tr>
<td>Phenol Producers</td>
<td>16</td>
</tr>
<tr>
<td>Overview of the Available Technologies for Managing Swine Wastes</td>
<td>17</td>
</tr>
<tr>
<td>Diet Modification</td>
<td>17</td>
</tr>
<tr>
<td>Wet Scrubbers</td>
<td>17</td>
</tr>
<tr>
<td>Pit Additives</td>
<td>18</td>
</tr>
<tr>
<td>Soil Filters</td>
<td>19</td>
</tr>
<tr>
<td>Chemical Addition</td>
<td>19</td>
</tr>
<tr>
<td>Chlorine and Lime</td>
<td>19</td>
</tr>
<tr>
<td>Potassium Permanganate</td>
<td>20</td>
</tr>
<tr>
<td>Hydrogen Peroxide</td>
<td>21</td>
</tr>
</tbody>
</table>
### CHAPTER

<table>
<thead>
<tr>
<th>Electrolytic Treatment</th>
<th>22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Covered Anaerobic Lagoon With Energy Recovery</td>
<td>23</td>
</tr>
<tr>
<td>Vermicomposting</td>
<td>24</td>
</tr>
<tr>
<td>Aerobic Treatment of Swine Wastes</td>
<td>26</td>
</tr>
<tr>
<td>Study Objective and Scope</td>
<td>28</td>
</tr>
</tbody>
</table>

### III. MATERIALS AND METHODS

- **Materials**
  - Swine Raising Facility | 32
  - Animals | 32
  - The Aeration System | 33
  - Flux Chambers | 33
  - Sampling Strategy | 34
  - Seeds | 36

- **Analytical Methods**
  - Respirometric Experiments | 37
  - Wastewater Analysis | 38
  - Gas Analysis | 38
  - Odor Panel | 39

### IV. RESULTS AND DISCUSSION

- **Respirometric Results** | 47
- **Water Quality Results** | 48
  - Dissolved Oxygen | 49
  - Nitrate | 50
  - Oxidation/Reduction Potential (ORP) | 51
  - pH | 52
  - Volatile Acids (VAs) | 53
  - Phenols | 54
  - Biochemical Oxygen Demand (BOD) | 56
  - Chemical Oxygen Demand (COD) | 57
  - Ammonia | 60
  - Alkalinity | 61
  - Orthophosphate (PO$_4^{3-}$) | 63
  - Total solids (TS) | 63
- **Air Quality Results** | 64
  - Ammonia | 64
  - Olfactory Evaluation | 65
CHAPTER V. ENGINEERING SIGNIFICANCE ............................................. 94

VI. CONCLUSIONS ........................................................................ 96

BIBLIOGRAPHY ......................................................................... 98

APPENDIX
A. PROPERTIES AND PHYSIOLOGICAL EFFECTS OF
   NOXIOUS GASES ................................................................... 106
B. PIG WEIGHT DATA ............................................................ 110
C. RAW DATA ........................................................................... 112
D. RAW WATER QUALITY DATA ............................................. 118
E. AVERAGED WATER QUALITY DATA ................................. 145
<p>|| TABLE | Page |
|-------|------|
| 2.1   | Tested Pit Additives | 31   |
| 3.1   | Wastewater analysis instrumentation and protocol | 45   |
| 4.1   | Average Odor Responses for Day 7 (High-Range Load) | 93   |
| 4.2   | Average Odor Responses for Day 7 (Low-Range Load) | 93   |
| A.1   | Properties and physiological effects of noxious gases (Adapted from Taiganides and White, 1968). | 107  |
| B.1   | Approximate pig weight data from 9/1/99 - 11/11/99 | 111  |
| B.2   | Approximate pig weight data from 2/3/00 - 5/10/00 | 111  |
| C.1   | Date and COD load for the control testing cycle | 113  |
| C.2   | Date and COD load for the aeration testing cycle | 114  |
| C.3   | Date and COD load for the aeration and seeding testing cycle | 114  |
| C.4   | Date and COD load for the low-range control testing cycle | 115  |
| C.5   | Date and COD load for the mid-range control testing cycle | 115  |
| C.6   | Date and COD load for the high-range control testing cycle | 115  |
| C.7   | Date and COD load for the low-range aeration testing cycle | 116  |
| C.8   | Date and COD load for the mid-range aeration testing cycle | 116  |
| C.9   | Date and COD load for the high-range aeration testing cycle | 116  |
| C.10  | Date and COD load for the low-range aeration and seeding testing cycle | 117  |
| C.11  | Date and COD load for the mid-range aeration and seeding testing | 117  |
| C.12  | Date and COD load for the high-range aeration and seeding testing cycle | 117  |
| D.1   | Raw water quality data for the control 9/22/99 - 9/29/99 | 119  |
| D.2   | Raw water quality data for the control 9/29/99 - 10/06/99 | 119  |
| D.3   | Raw water quality data for the control 11/03/99 - 11/10/99 | 120  |</p>
<table>
<thead>
<tr>
<th>TABLE</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>D.4</td>
<td>Raw water quality data for the control 2/10/00 - 2/17/00 121</td>
</tr>
<tr>
<td>D.5</td>
<td>Raw water quality data for the control 2/10/00 - 2/17/00 122</td>
</tr>
<tr>
<td>D.6</td>
<td>Raw water quality data for the control 3/15/00 - 3/22/00 123</td>
</tr>
<tr>
<td>D.7</td>
<td>Raw water quality data for the control 3/15/00 - 3/22/00 124</td>
</tr>
<tr>
<td>D.8</td>
<td>Raw water quality data for the control 5/4/00 - 5/11/00 125</td>
</tr>
<tr>
<td>D.9</td>
<td>Raw water quality data for the control 5/4/00 - 5/11/00 126</td>
</tr>
<tr>
<td>D.10</td>
<td>Raw water quality data for the control 5/24/00 - 5/31/00 127</td>
</tr>
<tr>
<td>D.11</td>
<td>Raw water quality data for the control 5/31/00 - 6/6/00 128</td>
</tr>
<tr>
<td>D.12</td>
<td>Raw water quality data for the control 6/14/00 - 6/21/00 129</td>
</tr>
<tr>
<td>D.13</td>
<td>Raw water quality data for the aeration with 15 minutes cycled on and off 10/06/99 - 10/13/99 130</td>
</tr>
<tr>
<td>D.14</td>
<td>Raw water quality data for the aeration 10/13/99 - 10/20/99 130</td>
</tr>
<tr>
<td>D.15</td>
<td>Raw water quality data for the aeration 10/20/99 - 10/27/99 131</td>
</tr>
<tr>
<td>D.16</td>
<td>Raw water quality data for the aeration 2/24/00 - 3/1/00 132</td>
</tr>
<tr>
<td>D.17</td>
<td>Raw water quality data for the aeration 2/24/00 - 3/1/00 133</td>
</tr>
<tr>
<td>D.18</td>
<td>Raw water quality data for the aeration 3/22/00 - 3/29/00 134</td>
</tr>
<tr>
<td>D.19</td>
<td>Raw water quality data for the aeration 3/22/00 - 3/29/00 135</td>
</tr>
<tr>
<td>D.20</td>
<td>Raw water quality data for the aeration 5/11/00 - 5/18/00 136</td>
</tr>
<tr>
<td>D.21</td>
<td>Raw water quality data for the aeration 5/11/00 - 5/18/00 137</td>
</tr>
<tr>
<td>D.22</td>
<td>Raw water quality data for the aeration 5/24/00 - 5/31/00 138</td>
</tr>
<tr>
<td>D.23</td>
<td>Raw water quality data for the aeration and seeding 10/27/99 - 11/03/99 139</td>
</tr>
<tr>
<td>TABLE</td>
<td>Description</td>
</tr>
<tr>
<td>-------</td>
<td>-------------</td>
</tr>
<tr>
<td>D.24</td>
<td>Raw water quality data for the aeration and seeding 3/1/00 - 3/8/00</td>
</tr>
<tr>
<td>D.25</td>
<td>Raw water quality data for the aeration and seeding 3/1/00 - 3/8/00</td>
</tr>
<tr>
<td>D.26</td>
<td>Raw water quality data for the aeration and seeding 4/12/00 - 4/19/00</td>
</tr>
<tr>
<td>D.27</td>
<td>Raw water quality data for the aeration and seeding 4/12/00 - 4/19/00</td>
</tr>
<tr>
<td>D.28</td>
<td>Raw water quality data for the aeration and seeding 5/31/00 - 6/6/00</td>
</tr>
<tr>
<td>E.1</td>
<td>Average water quality results for control, aeration, and aeration and seeding treatments for the low-range load</td>
</tr>
<tr>
<td>E.2</td>
<td>Average water quality results for control, aeration, and aeration and seeding treatments for the mid-range load</td>
</tr>
<tr>
<td>E.3</td>
<td>Average water quality results for control, aeration, and aeration and seeding treatments for the high-range load</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 Reaction scheme for anaerobic digestion</td>
<td>30</td>
</tr>
<tr>
<td>3.1 Swine raising facility</td>
<td>41</td>
</tr>
<tr>
<td>3.2 Hog's weight vs. time</td>
<td>42</td>
</tr>
<tr>
<td>3.3 The aeration system</td>
<td>43</td>
</tr>
<tr>
<td>3.4 Flux chamber</td>
<td>44</td>
</tr>
<tr>
<td>4.1 Respirometric Experiments on Swine Waste during Week 2</td>
<td>67</td>
</tr>
<tr>
<td>4.2 Respirometric Experiments on Swine Waste during Week 4</td>
<td>68</td>
</tr>
<tr>
<td>4.3 Respirometric Experiments on Swine Waste during Week 7</td>
<td>69</td>
</tr>
<tr>
<td>4.4 Dissolve oxygen vs. time for the low-range load</td>
<td>70</td>
</tr>
<tr>
<td>4.5 Dissolve oxygen vs. time for the mid-range load</td>
<td>70</td>
</tr>
<tr>
<td>4.6 Dissolve oxygen vs. time for the high-range load</td>
<td>71</td>
</tr>
<tr>
<td>4.7 Nitrate concentration vs. time of the low-range load</td>
<td>71</td>
</tr>
<tr>
<td>4.8 Nitrate concentration vs. time for the mid-range load</td>
<td>72</td>
</tr>
<tr>
<td>4.9 Nitrate concentration vs. time for the high-range load</td>
<td>72</td>
</tr>
<tr>
<td>4.10 ORP level vs. time for the low-range load</td>
<td>73</td>
</tr>
<tr>
<td>4.11 ORP level vs. time for the mid-range load</td>
<td>73</td>
</tr>
<tr>
<td>4.12 ORP level vs. time for the mid-range load</td>
<td>74</td>
</tr>
<tr>
<td>4.13 pH vs. time for the low-range load</td>
<td>74</td>
</tr>
<tr>
<td>4.14 pH vs. time for the mid-range load</td>
<td>75</td>
</tr>
<tr>
<td>4.15 pH vs. time for the high-range load</td>
<td>75</td>
</tr>
<tr>
<td>4.16 Volatile acids concentration vs. time for the low-range load</td>
<td>76</td>
</tr>
<tr>
<td>4.17 Volatile acids concentration vs. time for the mid-range load</td>
<td>76</td>
</tr>
<tr>
<td>FIGURE</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>4.18</td>
<td>Volatile acids concentration vs. time for the high-range load</td>
</tr>
<tr>
<td>4.19</td>
<td>Phenol concentration vs. time for the low-range load</td>
</tr>
<tr>
<td>4.20</td>
<td>Phenol concentration vs. time for the mid-range load</td>
</tr>
<tr>
<td>4.21</td>
<td>Phenol concentration vs. time for the high-range load</td>
</tr>
<tr>
<td>4.22</td>
<td>Normalized BOD vs. time for the low-range load</td>
</tr>
<tr>
<td>4.23</td>
<td>Normalized BOD vs. time for the mid-range load</td>
</tr>
<tr>
<td>4.24</td>
<td>Normalized BOD vs. time for the high-range load</td>
</tr>
<tr>
<td>4.25</td>
<td>BOD concentration vs. time for the low-range load</td>
</tr>
<tr>
<td>4.26</td>
<td>BOD concentration vs. time for the mid-range load</td>
</tr>
<tr>
<td>4.27</td>
<td>BOD concentration vs. time for the high-range load</td>
</tr>
<tr>
<td>4.28</td>
<td>COD concentration vs. time for the low-range load</td>
</tr>
<tr>
<td>4.29</td>
<td>COD concentration vs. time for the mid-range load</td>
</tr>
<tr>
<td>4.30</td>
<td>COD concentration vs. time for the high-range load</td>
</tr>
<tr>
<td>4.31</td>
<td>Normalized COD vs. time for the low-range load</td>
</tr>
<tr>
<td>4.32</td>
<td>Normalized COD vs. time for the mid-range load</td>
</tr>
<tr>
<td>4.33</td>
<td>Normalized COD vs. time for the high-range load</td>
</tr>
<tr>
<td>4.34</td>
<td>Ammonia concentration vs. time for the low-range load</td>
</tr>
<tr>
<td>4.35</td>
<td>Ammonia concentration vs. time of the mid-range load</td>
</tr>
<tr>
<td>4.36</td>
<td>Ammonia concentration vs. time for the high-range load</td>
</tr>
<tr>
<td>4.37</td>
<td>Alkalinity concentration vs. time for the low-range load</td>
</tr>
<tr>
<td>4.38</td>
<td>Alkalinity concentration vs. time for the mid-range load</td>
</tr>
<tr>
<td>4.39</td>
<td>Alkalinity concentration vs. time for the high-range load</td>
</tr>
<tr>
<td>4.40</td>
<td>Orthophosphate concentration vs. time for the low-range load</td>
</tr>
<tr>
<td>4.41</td>
<td>Orthophosphate concentration vs. time for the mid-range load</td>
</tr>
<tr>
<td>4.42</td>
<td>Orthophosphate concentration vs. time for the high-range load</td>
</tr>
<tr>
<td>4.43</td>
<td>Total solids concentration vs. time for the low-range load</td>
</tr>
<tr>
<td>4.44</td>
<td>Total solids concentration vs. time for the mid-range load</td>
</tr>
<tr>
<td>FIGURE</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>4.45</td>
<td>Total solids concentration vs. time for the high-range load</td>
</tr>
<tr>
<td>4.46</td>
<td>Air phase ammonia vs. time for the low-range load</td>
</tr>
<tr>
<td>4.47</td>
<td>Air phase ammonia vs. time for the mid-range load</td>
</tr>
<tr>
<td>4.48</td>
<td>Phenol concentration vs. dissolved oxygen concentration</td>
</tr>
<tr>
<td>4.49</td>
<td>Oxidation/reduction potential vs. ammonia concentration</td>
</tr>
</tbody>
</table>
CHAPTER I
INTRODUCTION

Problem Statement

The swine industry has a significant economic and agricultural importance in the States of Iowa, North Carolina, and Mississippi. By the end of 1994, North Carolina had over seven million hogs raised by the swine industry which gave it the distinction of being the second leading hog producing state, trailing Iowa (Vukina, et al., 1996). The North Carolina swine operations are generally large scale operations which often include over 500 hogs at each site (Vukina, et al., 1996). This important economic activity generates an estimated $1.3 billion annually for the State of North Carolina (Herrera, 1999). Likewise, the swine industry can potentially be of significant agricultural importance to the State of Mississippi (Zappi, et al., 2000).

Over the past five decades, there have been major changes in swine production including a reduction in the number of farms, a dramatic increase in the number of hogs at each facility, and the change from open to confined production. Originally, swine raising was operated as a family business (Kennedy, 1999). The traditional, small family-run farm operations, where a few pigs are raised to supplement other agricultural operations, have rapidly declined (Miner, 1999). According to Thompson (1999), the swine industry is
controlled today by a few large companies which has driven down the market price. Thus, small hog farming operations are virtually unprofitable within today’s market.

During the last twenty years, the number of hog farmers in the United States has dropped by fifty percent (O’Brien, 1995). By 1992, only 5 percent of the U.S. farmers who once raised hogs still raised hogs (Thompson, 1999). This reduction in the number of swine producers has been occurring since early in the twentieth century (Coffey, 1999). Nevertheless, the total number of head produced annually in the U.S. has remained relatively constant over the period ranging from 1988 to 1994 (7,626,000 and 7,673,000 head, respectively [Atkinson and Watson, 1996]).

As stated earlier, the swine industry has evolved into a corporate and industrialized production entity. The result is that the swine industry is in the process of experiencing major structural changes including corporate ownership, vertical integration, total confined housing, and contract farming (Merlo, 1999). These structural changes have evolved as the result of economic, political, and social forces. New technology and the economics of scale have influenced the concentration of integrated swine production (Coffey, 1999).

Swine production today may be viewed by local populations as being operated by outsiders. This results from the fact that corporate owners may be hundreds of miles away. Only essential operating personnel can be found on site. On-site employees may be local residents, but often, they are new immigrants (Miner, 1999). This allows wage-based costs to be kept at a minimum.

There are numerous environmental concerns that may result from concentrated swine production activities. Objectionable odors have always been linked to livestock production
In recent years, the management of unpleasant odors has become a major environmental challenge for confined animal production (Casey and Hobbs, 1994). In traditional farming, swine were raised at low density with little odor being produced, because a vegetative ground cover, such as grass, was maintained. Under these conditions, the manure was widely dispersed and dried quickly in the open air. Odorous compounds in the urine and feces were incorporated into the soil and quickly degraded, often under aerobic conditions. This resulted in odor and pollution free manure management using natural decomposition (Miner, 1974).

There are several sources of odors originating from swine-raising facilities including feces on the floor, underdrain storage areas, anaerobic lagoons, lagoon effluents irrigated onto ground surfaces (often supporting forage crops), and dead animals (Miner, 1999). Swine wastes are primarily a mixture of urine, feces, undigested food, and bacteria from the lower gastrointestinal tract of the swine (Sutton et al., 1999). Manure contains a variety of simple to complex organic compounds, inorganic compounds, and possibly, feed additives. Once the feces from the pigs are excreted, odorous organic compounds (VOCs), such as short-chain of volatile fatty acids (VFA), and other volatile carbon-, nitrogen- and sulfur-containing compounds from anaerobic microbial fermentation within the gastrointestinal tract (GIT), may be emitted (Sutton et al., 1999). The fermentative decomposition of fecal substances is activated by anaerobic bacteria which produce highly odorous, VOCs as by-or end-products (Zhu and Jacobson, 1999).

According to Zhang and Day (1996), hydrogen sulfide and ammonia are the main odor compounds associated with swine facilities. Ammonia is generated during the
anaerobic degradation of nitrogenous compounds in the feces, waste feed which collects in
the pits, and the urea within urine. The lack of proper odor control can often be related to
a lack of knowledge of the fundamental nature of livestock-derived odors (Mackie, 1998).

Current crop-based U.S. farming practices use chemical fertilizers, not organic
fertilizers such as hog manure. This has resulted in a situation in which swine and crop
production are not integrated nor interdependent (Morse, 1995). Thus, animal manure is
neither popular nor in demand for its fertilizer value. Originally, the term manure was used
to describe excreta that was primarily used as a fertilizer and soil conditioner. However,
manure is now considered a pollutant and nuisance (Williams, 1995). The swine farmer is
now considered to be a major contributor to local and regional environmental pollutions
(Herrera, 1999).

Most swine are raised on top of slotted gratings which are suspended over
underdrains filled with water. The underdrains are utilized for manure collection and
storage. This results in the generation of large amounts of liquid wastes with highly,
objectionable odors. While in storage, anaerobic decomposition of the manure produces
gases, such as ammonia, methane, hydrogen sulfide, and carbon dioxide, which are released
into the atmosphere. Ammonia and hydrogen sulfide, because of their irritating and toxic
nature, are the two gases of major concern to the health of workers and animals within indoor
containments (Donham, 1990).

The current disposal practice for wastewater generated within the underdrain pits
(which contain 0.5-3.0% solids) from large production facilities is to channel it into large
anaerobic lagoons. Over a two- to six-month period within the lagoons, the pollutants within
the wastewater are decomposed via anaerobic biodegradation. This effluent is then sprayed onto fields typically supporting forage crops (Herrera, 1999). However, during this application, obnoxious odors can carry for miles and last for several days. Thus, neighboring areas often develop a resentful mood towards the facility due to these often strong odors (Foster, 1996).

Odors can have a great negative impact on the general well-being of the public. Odors can affect both the physiological and psychological condition of humans (Rotton, 1983). Odorous compounds may be carried in a plume without significant reduction at distances up to 1,500 feet or greater downwind from a source (Gassman, 1992). Dispersion models are now available that can predict the peak and mean concentrations of odors and environmental air pollutants at varying distances from the source (Cha and Brown, 1992).

Unpleasant odors have been traced to problems such as personal discomfort, allergic responses, impaired respiration, loss of appetite, decreased liquid consumption, loss of sleep, mental stress, nausea, vomiting, increased levels of tension, depression, anger, and fatigue (Schiffman, et al., 1994). Miner (1980) adds depression and annoyance to this list. However, there is no proven relationship between odors and a specific disease or toxicity of a gas (Mosier et al., 1973).

Nasal and respiratory irritation can result from odorant molecules from hog farms (Bundy, 1992). Nasal irritation can elevate adrenalin which may contribute to feelings of tension and anger (Allison and Powis, 1976). The VOCs responsible for odors also may be absorbed directly into the bloodstream and fat stores of the body by gas exchange within the lungs. Research has shown that many VOCs inhaled in the lungs also reach blood and
adipose tissue (Ashley et al., 1994; Artis and Silvester, 1986). Persons who have absorbed odorants into their lungs can often smell the odor for hours after exposure, which is due to the slow release of the odorants from the bloodstream into expired air (Raymer et al., 1991).

Even low level amounts of culprit compounds associated with swine production may continue to generate public complaints, if their concentrations are above odor thresholds (Carney and Dobb, 1989). Throughout the United States, residents complain about odors as the single most uncontrollable and controversial air pollution problem associated with animal production, particularly swine (Kreis, 1978). In an effort to control agricultural pollution, legislation is under consideration in the United States that will probably restrict agricultural practices and penalize farmers when they exceed set limits of waste disposal (Mackie, 1998).

Animal production has also recently developed within close proximity to population centers and major markets where land values are expensive. Complaints from neighbors on non-health related issues due to livestock odors include reduced property values and deprivation of the desired use of the odor infringed-upon property. This has directly effected the increased frequency of odor related lawsuits within areas of concentrated swine production (Zhu et al., 1997; Macki, 1998). Public complaints concerning odors from swine operations usually focus on reduced property values and the qualify of life (Coffey, 1999).

In North Carolina, critics of the swine industry’s rapid expansion argue that laxed environmental regulations promote ground and surface water pollution. The strongest public complaints focus on offensive odors released from the barns and manure collecting lagoons from large hog operations. The public complains that swine odors affect the quality of their
lives, may cause yet unknown long term health problems, and reduce real estate property
values (Vukina et al., 1996)

Generally, the ownership of land includes the right to release odors into the air, dust
and smoke, and make noise, provided these actions do not interfere with the comfort of
others or effect the use and enjoyment of their property. When in violation of this principle,
a person may be guilty of creating a nuisance. Thus, this principle of nuisance acts as a
restriction and can be applied to unreasonable, unwarranted, or unlawful use of property to
produce annoyance, inconvenience, discomfort, or hurt that the law could presume to be a
damage in a lawsuit. What constitutes a nuisance in each case must be decided based upon
the particular facts and circumstances (Miner, 1978).

Swine industries are important to the U.S. economy. Pork is one of the main diets
of our population. As the population increases, the demand of pork will be increased, and
the people are invading the countryside closer to where the swine industries are located.
Thus, coexistence between the swine industries and human who live side by side in the future
is inevitable. However, swine wastes that are left untreated are polluting the environment.
The odors that are generated from the swine wastes are causing many health problems to the
people who live nearby. Many attempts that had developed in the past to correct those
problems were not economically feasible for the swine industries. The purpose of this study
was to study the dynamics of chemical changes within the underdrain and evaluate the
benefits of turning the underdrains from an anaerobic environment to an aerobic environment
by aerating it with the atmospheric air. Aerobic treatment has been used extensively by the
U.S. municipal wastewater treatment plants to treat domestic wastewater. Its advantage is
to provide faster treatment with minimal release of unpleasant odors compared to the anaerobic treatment (Metcalf and Eddy, 1991).
CHAPTER II

LITERATURE REVIEW

Introduction

Historically, research focused on swine odor management has garnered little attention and funding. Within the last few years, millions of dollars have been made available to many universities across the United States for research to solve swine odor management problems. Researchers from private organizations and universities have joined together to develop solutions to odor problems. They have developed many chemical and physical methods to reduce odors from manure storage and animal raising facilities; however, these methods have generally proven to be too expensive for hog producers. As a result, storage of wastes within underdrains coupled with anaerobic treatment within lagoons still remains the current practice for water treatment, with no real additional technology used for odor abatement/management. However, usage of underdrains, lagoon treatment, and the associated irrigation of effluent often results in odor generation. These techniques all use or are associated with anaerobic biodegradation, which produces odors. Therefore, aerobic treatment may be an attractive option for controlling odor problems (McMahon, 1996). aerobic biotreatment has been successfully used to treat domestic wastewater, as well as industrial wastewater, with little or no odors produced (Metcalf and Eddy, 1991).
The end products of anaerobic catabolism are methane, H\textsubscript{2} and CO\textsubscript{2}. According to the Energy Information Administration or EIA (1997), carbon dioxide and methane account for 84 percent and 9 percent of U.S. greenhouse gas emissions, respectively. Furthermore, waste management activities are the single largest source of methane emissions within the U.S. Nearly 30 percent is estimated to come from agricultural activities with more than 95 percent of all methane emissions from agriculture being attributable to livestock management. Almost two-thirds of emissions from livestock management results from the anaerobic digestion. Also, EIA (1997) suggests that if wastewater can be treated aerobically, methane emissions will be minimal; thereby, eliminating a substantial flux of greenhouse gases into the atmosphere.

**Anaerobic Lagoons-Current Practice**

Within anaerobic lagoons, because aeration is not provided for waste treatment, anaerobic microbial activity quickly establishes. The waste influent generally is handled as a thick slurry or as a very moist solid. Anaerobic lagoons have been used in animal waste management systems since the late 1950s as a cost effective means of treating wastes (Miner, 1978). Severe odor problems can be associated with this type of treatment (Metcalf and Eddy, 1991).

Anaerobic lagoons serve as a primary containment for solid wastes where a high level of solids breakdown to liquid effluent is achieved. This effluent is used as irrigation fluids to forage crop cultivation fields using conventional irrigation equipment (Miner, 1974). When the effluent is spread on land as fertilizer, the odorous stench carries for miles and lasts for
days, leaving those who live nearby in a resentful mood. (Foster, 1996).

Anaerobic lagoons have recently gained additional negative attention because new real estate developments are rapidly expanding into the countryside where swine-raising facilities have traditionally operated. Complaints and lawsuits by neighbors (often former urban dwellers) have turned legal attention toward odors and methods of controlling them. Other concerns are associated with air quality for those who work in the buildings and the hogs themselves. Therefore, a cost effective method is needed for managing swine waste (Fulhage, 1993).

**Odor Formation In Anaerobic Lagoons**

Odors associated with anaerobic lagoons have been described in a broad range, from non-offensive to highly offensive. Generally, offensiveness is in “the eye of the beholder.” In other words, the basis for determining whether an odor is offensive or not is often influenced by a person’s background. In general, people with agricultural backgrounds are more likely to be familiar with the agricultural odors and as such find these odors less offensive (McFarland and Easterling, 1996). A lagoon containing a large concentration of fresh manure is high in easily decomposable, organic matter that the anaerobic bacteria readily decompose into odorous by-products that are relatively volatile (Miner, 1974). Appendix A summarizes some pertinent properties and physiological effects of odorous chemicals often associated with swine waste (Fulhage, 1993). A complete listing of gases and odors that commonly released from confined facilities due to the action of bacteria on biodegradable components of swine wastes are listed in Appendix A.
Organic substances that also greatly contribute to the odorous aspect of gases within swine buildings are amines, mercaptans, alcohols, carbonyls, and sulfides. These are often present in trace amounts. However, because the human nose is extremely sensitive to these compounds, these gases are of primary concern, even though they are usually present at trace amounts (Fulhage, 1993).

**Key Anaerobic Reactions**

Anaerobic degradation of complex wastes, such as animal manure, is an inter-related, multistaged microbial process of serial and parallel reactions (Zeikus, 1979; Zinder, 1984). Figure 2.1 details the most probable reaction scheme for anaerobic degradation of organic animal-based wastes (Pavlostathis and Gosset, 1986). Manure is composed of various organic fractions such as carbohydrate, proteins, and lipids. Under appropriate redox, moisture, and temperature conditions, manure is subject to anaerobic bacterial degradation which results in the generation of odorous volatile compounds (Tamminga, 1992). Each component of the manure (carbohydrate, proteins, and lipids) goes through three degradation stages: hydrolysis, fermentation, and methane production. These stages are performed by: (1) fermentative or acid-forming bacteria; (2) hydrogen-producing acetogenic bacteria; (3) acetoclastic methanogens; and (4) carbon dioxide-reducing methanogenic bacteria (Masse and Droste, 1999). Equations 1 to 3 are used by fermentative bacteria in the anaerobic degradation of sugar molecules into acetic acids, propionic acids, and butyric acids, respectively.

\[
C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2 \quad \text{Equation 1}
\]
\[ C_6H_{12}O_6 + 2H_2 \rightarrow 2CH_3CH_2COOH + 2H_2O \]  
Equation 2

\[ C_6H_{12}O_6 \rightarrow 2CH_3CH_2CH_2COOH + 2CO_2 + 2H_2 \]  
Equation 3

Propionic and butyric acids are subsequently converted to acetic acids releasing hydrogen and carbon dioxide as shown in Equations 4 and 5.

\[ CH_3CH_2COOH + 2H_2O \rightarrow CH_3COOH + CO_2 + 3H_2 \]  
Equation 4

\[ CH_3CH_2CH_2COOH + 2H_2O \rightarrow 2CH_3COOH + 2H_2 \]  
Equation 5

Hydrogen and carbon dioxide are combined to form methane and water by the methanogens (Equation 6).

\[ CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \]  
Equation 6

Acetic acid is then broken down into methane and carbon dioxide by acetoclastic methanogens (Equation 7).

\[ CH_3COOH \rightarrow CH_4 + CO_2 \]  
Equation 7

The sugar, organic acids, carbon dioxide, and hydrogen combined with a nitrogen source, such as ammonia, are utilized by bacteria for cell growth. The mechanism shown in Equation 8 are performed by acid-forming bacteria that utilize glucose and ammonia to form cell mass and water.

\[ 5C_6H_{12}O_6 + 6NH_3 \rightarrow 6C_5H_7NO_2 + 18H_2O \]  
Equation 8

Equations 9 and 10 show mechanisms used by acetogenic bacteria to convert propionic, butyric acids, and ammonia to cell mass and other by-products.

\[ 3CH_3CH_2COOH + CO_2 + 2NH_3 \rightarrow 2C_5H_7NO_2 + 2H_2O + H_2 \]  
Equation 9
\[
\text{CH}_3\text{CH}_2\text{CH}_2\text{COOH} + \text{CO}_2 + \text{NH}_3 \rightarrow \text{C}_3\text{H}_7\text{NO}_2 + 2\text{H}_2\text{O}
\]  
Equation 10

Equation 11 is performed by acetoclastic bacteria that use acetic acid and ammonia to synthesize their cell mass and water.

\[
5\text{CH}_3\text{COOH} + 2\text{NH}_3 \rightarrow 2\text{C}_3\text{H}_7\text{NO}_2 + 6\text{H}_2\text{O}
\]  
Equation 11

Equation 12 is performed by hydrogen-utilizing bacteria that use carbon dioxide, hydrogen, and ammonia to synthesize cell mass and water.

\[
5\text{CO}_2 + 2\text{H}_2 + \text{NH}_3 \rightarrow \text{C}_3\text{H}_7\text{NO}_2 + 8\text{H}_2\text{O}
\]  
Equation 12

Acid-Forming Bacteria

According to Gaudy and Gaudy (1980), acid-forming bacteria produce extracellular enzymes which break down carbohydrates, proteins, and lipids to produce soluble sugars, amino acids, and fatty acids, respectively. In turn, the acid-producing bacteria transform these intermediates into acetic, propanoic, butanoic acids, hydrogen, and carbon dioxide. The metabolic pathways which fermentative bacteria convert proteins and lipids into VFA are not well known; however, the metabolic pathways for the conversion of carbohydrate to VFA are well understood (McInerney, 1998). Equations 1-3 detail the stoichiometry of glucose metabolism into acetic, propanoic and butanoic acids, respectively, by the Embden-Meyerhof pathway (Mosey, 1983).

Hydrogen-Producing Acetogenic Bacteria

The second key group of bacteria is the hydrogen-producing acetogenic bacteria which oxidize fatty acids with molecular weights higher than acetic acid to produce acetic
acid, hydrogen, and carbon dioxide (Zinder, 1984). Propanoic and butanoic acids are converted to acetic acid following the mechanisms listed as Equations 4 and 5. Acetic acid is then converted into methane and carbon dioxide via Equation 6 and cell mass according to Equation 11. Hydrogen and carbon dioxide are utilized with ammonia to form cell mass via Equation 12.

Acetoclastic Methanogens

The third group of bacteria is the acetoclastic methanogens: *Methanosaeta* and *Methanosarcina*. This group of bacteria breaks down acetic acid into methane and carbon dioxide (Masse and Droste, 1999). The reaction for this conversion is described in Equation 7. According to Mah et al. (1980), approximately 75% of the methane produced during anaerobic degradation comes from the conversion of acetic acid. Furthermore, Masse and Droste (1999) interpreted the work of Jetten et al. (1990) and McCarty and Mosey (1991) and came to a conclusion which suggests that both *Methanosaeta* and *Methanosarcina* are present in most anaerobic reactors.

Carbon Dioxide-Reducing Methanogens

Hydrogen-utilizing methanogens are members of the last group of the bacteria listed in Figure 2.1. Equation 6 presents the reaction mechanism for this conversion. Species that have been found to reduce carbon dioxide to methane are *Methanobacterium omeliansk, M. formicium, Methanococcus vannielli,* and *Methanosarcian barkerii*. About 25% of methane produced is generated by these bacteria (Jeris and McCarty, 1965; Mah et al., 1980; Pelczar
et al., 1986).

*Sufuromonas*

This group is comprised of anaerobic bacteria that respire anaerobically by using inorganic sulfur compounds as electron acceptors resulting in the formation of large amounts of $\text{H}_2\text{S}$. One genus, *Sufuromonas*, uses elemental sulfur as its electron acceptor. The other genera cannot use elemental sulfur, but effectively utilize sulfate, thiosulfate, or other oxidized sulfur compounds. Two genera in this group are *Desulfovibrio*-vibrioid (or helical cells), and *Desulfococcus*-spherical cells (Pelczar et al., 1986). The production of volatile sulfur-containing compounds, such as sulfides and methyl/ethyl-mercaptans, results from sulfate reduction and the metabolism of sulfur-containing amino acids, such as cysteine and methionine. The bacterial genera associated with this activity include *Desulfovibrio*, *Megasphaera*, and *Veillonella* (Hao et al. 1996).

**Phenol Producers**

Indole and phenols are present in freshly excreted feces and urine and continue to form during the anaerobic degradation of tyrosine, and phenylalanine within swine waste (Ishaque et al., 1985; MacFarlane and MacFarlane, 1995; Mackie, 1994). They are a major component in malodor formation within confinement swine buildings and stored wastes. Phenol are readily oxidized under aerobic conditions (Ishaque et al., 1985). It can also be degraded anaerobically by a *Clostridium* species (Fuchs, 1994). Tyrosine and phenylalanine are the two aromatic amino acids that are metabolized by the following genera: *Bacteroides*,
Bifidobacterium, Clostridium, Eubacterium, Escherichia, Lactobacillus, and Propionibacterium (Mackie, 1998; Zhu and Jacobson, 1999).

Overview of the Available Technologies for Managing Swine Wastes

There are many technologies available on the market that claim to control swine odor. These technologies utilize chemical, physical, and/or biological techniques. Also, a combination of two or more, or all of the above technologies can be used. Nevertheless, in many cases, these technologies have been found to be cost prohibitive for the typical swine farmer. Alternative methods of odor control are needed which combine reasonable cost with commonly practiced management skills at the same time meeting odor reduction objectives.

Diet Modification

Because some odorous compounds result from anaerobic degradation of carbohydrate and protein, diet modifications have been proposed to enhance in vivo utilization of nutrients, thus reducing nutrient excretion. By regulating the diet to modify the microbial activity in the lower GIT, the excretion of odor-causing compounds can be reduced because the nutrient intake is matched with the nutrient usage by the animal (Sutton et al., 1999). Additionally, formulating diets to accurately meet amino acid requirements can reduce the excretion of nutrients (Coffey, 1999). The Swine Odor Task Force (1995a) reported that the use of odor control additives could be employed to reduce odor production. However, the reformulation of diets is in the developmental stage and has not been successfully used to date on the full farm scale.
Wet Scrubbers

A wet pad scrubber for removing dust and odors from ventilation exhaust has been designed for use in tunnel-ventilated swine buildings (Bottcher et al., 1999a). The scrubber is comprised of an evaporative cooling pad system with water recirculation. In warm weather, this system provides modest reductions of dust and odor emissions. It represents a dust and odor control method which does not substantially challenge exiting ventilation systems by causing excessive headloss. This system also appears to be reasonably affordable for producers. The installation cost being $5.70 per unit for an 880-head finishing area. The main operating cost being the 1 hp water pump which is estimated to have an annual cost of approximately $600. Additional study is needed to fully characterize performance of this system over a range of ambient conditions and pig ages (Bottcher et al., 1999b).

Pit Additives

In order to avoid environmental pollution, obviously odors and other volatile substances in swine waste need to be treated before release into the environment. One type of treatment involves the addition of amendments into the pit which prevent odor formation. Laboratory experiments conducted by Zhu et al. (1997) tested the commercial pit additives listed in Table 2.1. The results show that all of the pit treatments significantly reduced odorous levels (by 58-87%). Nevertheless, MPC, Bio-Safe, and Shac were more effective than the other two in terms of reducing the total amount of released volatile acids (14%, 10%, and 23%). However, the abatement of ammonia and hydrogen sulfide emissions from swine manure was not evident for any of the treatments tested in this study.
Soil Filters

Hydrogen sulfide and ammonia from animal waste have been successfully removed by soil filters (Burnett and Dondero, 1969). The use of soil filters was effective in removing both hydrogen sulfide and ammonia from the head-space gas over decomposing poultry manure. Throughout three months of continuous testing, the complete removal of ammonia concentrations up to 200 ppm was reported. The removal of hydrogen sulfide levels as high as 100 ppm was reported as 95 percent successful. However, when the soil columns dried, the ammonia removal efficiency dropped rapidly. Therefore, the moisture content of the soil must be maintained to be totally effective. The moisture-holding capacity was increased by mixing manure with the soil prior to using it in the column. (Burnett and Dondero, 1969).

Chemical Addition

Miner (1974) reported that there are some relatively inexpensive chemicals that can be added to manure to achieve odor control. With this approach, a chemical or a mixture of chemicals is typically added first to stop the anaerobic decomposition. The addition of oxygen to the water reduces anaerobic activity, while stimulating aerobes to degrade many of the odorous chemical compounds.

Chlorine and Lime

Chlorine and lime have been successfully used to deodorize liquid hog manure (Miner, 1974). Results showed that chlorine and lime can be added to successfully inactivate anaerobic bacteria. This research established a daily demand of chlorine and lime at 50 g and
80 g, respectively, per 50 kg of swine weight (Day, 1966). However, other literature has shown that by adding chlorine, the pH will decrease resulting in the formation of odorous compounds from volatile acids via hydrolysis (Miner, 1974). On the other hand, by adding lime, the pH will increase possibly resulting in the formation of odorous compounds, such as ammonia and other amines. Therefore, both processes may have an adverse impact on the health of the animals and the workers.

Potassium Permanganate

Potassium permanganate (KMnO₄) is a very strong oxidizing agent. Permanganate (MnO₄⁻) solutions are effective as oxidizing agents for odor control in acidic and alkaline solutions (Miner 1974). However, potassium permanganate is least effective in neutral solutions. Three different oxidation reactions can occur, depending on the pH of the solution, as shown below:

In strongly acidic (pH < 2),

\[
\text{MnO}_4^- + 8\text{H}^+ + 5\text{e}^- \rightarrow \text{Mn}^{2+} + 4\text{H}_2\text{O} \quad \text{Equation 13}
\]

In more neutral solutions (pH 3-11),

\[
\text{MnO}_4^- + 6\text{H}^+ + 5\text{e}^- \rightarrow \text{MnO}_2 + 3\text{H}_2\text{O} \quad \text{Equation 14}
\]

In strongly alkaline solutions (pH 11),

\[
\text{MnO}_4^- + 6\text{H}^+ + 7\text{e}^- \rightarrow \text{MnO}_2^+ + 3\text{H}_2\text{O} \quad \text{Equation 15}
\]

The most effective reaction, in practical application, is Equation 14, because the solution is essentially noncorrosive. In all three reactions, the reaction rate will increase with
increasing temperature, increasing KMnO₄ concentration, and increasing concentration of oxidizable compounds. Also, the rate of reaction increases as the pH varies from neutral in either direction.

Potassium permanganate has been recommended for odor control around livestock production facilities since the 1960's (Faith, 1964). The oxidizing capabilities of potassium permanganate, when used in gas-scrubbing devices, have been documented (Posselt and Reidies, 1965). In their studies, air containing various odorants was passed through a pair of gas-washing bottles placed in parallel. One gas-washing bottle contained a one percent solution of potassium permanganate at a pH of 8.5. The other bottle contained distilled water at a similar pH. Under these conditions, a comparison was made of the threshold odor numbers of the effluents from the two bottles when various odorous organic compounds were passed through each solution. They evaluated the effectiveness of potassium permanganate for the oxidation of mercaptans, amines, phenols, and other organic odorants. In each case, they found a significant reduction in the threshold odor number was achieved by passing the gases through the potassium permanganate solution in comparison to passing the gases through the distilled water.

Hydrogen Peroxide

The use of hydrogen peroxide has been proposed for various waste treatment applications (Miner 1974). Hydrogen peroxide (H₂O₂) is commercially available as an aqueous solution ranging from three percent (used as a disinfectant in first aid) to 70 percent solutions used for industrial application. It's primary function is as an oxidizing agent;
however, it also provides oxygen, thus inhibiting anaerobic activity. Hydrogen peroxide decomposes to form water, molecular oxygen, and an accompanying release of heat. Strong solutions, having greater than eight percent H$_2$O$_2$ are considered corrosive and must be handled in specially selected materials. The biotic decomposition of hydrogen peroxide is

\[ 2\text{H}_2\text{O}_2 \rightarrow 2\text{H}_2\text{O} + \text{O}_2 + \text{heat} \quad \text{Equation 16} \]

The use of hydrogen peroxide for controlling swine manure odors was documented during the early 1970s ( Miner 1974). Pig manure slurry was treated with a stock 10 percent hydrogen peroxide solution diluted to levels of 115 and 275 ppm. At this level, the hydrogen peroxide serves as an oxygen source. Hydrogen peroxide was fed into the open end of the discharge pipe as the manure was pumped from a holding pit into a 5.3 m (1,400 gal.) liquid manure tank. Hydrogen sulfide levels were reduced to zero in the gas over the manure slurry under both test conditions. The investigator, however, concluded that superior odor control was obtained using the 115 ppm dosage. The reason for this increased effectiveness was considered to be primarily a result of the effective mixing that took place in the trial. Headspace hydrogen sulfide was present at a level of 10 ppm in the holding tank, but after treatment, was reduced to zero (O’Neil, 1972).

**Electrolytic Treatment**

This innovative technique was developed to control noxious odors by using a low voltage current in stored slurries to hinder bioactivity (Chiumenti et al., 1988; Donantoni and Soriato, 1995). According to Matsunaga et al. (1984), an electric current has an inhibitory effect on the activity of microbial cells. The electric current alters the chemosmotic
mechanisms of a cell membrane inhibiting ATP synthesis and cell metabolism of the anaerobic respiration. Thus, fermentative activity and anaerobic respiration can be reduced, which in turn, will reduce noxious gas formation. Also, it was reported that an electric current can induce metal salts to form a complex with odorous molecules into non-volatile compounds. Furthermore, the application of electric current stimulates the migration of ions in relation to their electric charge reducing their reciprocal attraction, therefore, reducing the formation of surface crust and coarse solids. Nevertheless, the expense of this treatment proved to be excessive and is beyond practical use by swine operations (Ranalli et al., 1996).

Covered Anaerobic Lagoon With Energy Recovery

Cheng et al. (1999) reports the practical application of a covered anaerobic lagoon on a farrow-to-wean swine farm with 4,000 sows in two farrowing houses and four gestation houses. A pit-recharge system was used for collecting manure from the houses (eight pits per house). The full volume for each pit was 5,000 gallons in the gestation houses and 7,800 gallons in the farrowing houses. Two lagoons in series were used for waste management, including a covered anaerobic lagoon for primary waste treatment and a variable volume storage lagoon. One pit was discharged into the covered anaerobic lagoon and recharged daily with water from the storage lagoon in each house. The covered, anaerobic lagoon had a surface area of 265 ft. x 265 ft. and a depth of 20 ft. with a wall slope of 3:1. The storage lagoon had a surface area of 240 ft. x 1,070 ft. and a water level of about 8 ft. The designed hydraulic retention time in the covered, anaerobic lagoon was 65 days with a loading rate of 9 lbs. VS/1000 ft³-day. The design was met the designated hydraulic criteria established
under NRCS Interim Standard No. 360. This system was started in December 1996 using a high density polyethylene, factory fabricated, modular cover. Under specified conditions, an electric generator operated with the combustion of biogas produced from the covered anaerobic lagoon and waste heat collected from the engine exhaust and radiator to heat a 10,000 gallon water tank providing heat to the farrowing houses. The cover collected up to 1,200 ft³/hr of biogas for use in the generator until fabrication and material problems resulted in air infiltration. The cover was replaced under manufacturer’s warranty in November 1997. However, the new cover experienced the same problems. As a result of these problems, a new design of bank-to-bank cover with a high density polyethylene material was installed in July 1998. The covered anaerobic lagoon system has performed well since then with the added benefit of eliminating rainwater from the primary treatment lagoon.

**Vermicomposting**

Research has shown that earthworms play an effective role in the decomposition of organic wastes and residues (Edwards, 1998). Earthworms have been used to process almost every conceivable organic waste and convert it into fine particulate matter called castings. For example, earthworms have been used in the management of materials such as municipal sewage sludge, brewery wastes, potato wastes, paper waste, mushroom wastes, horticultural residues, and a wide variety of animal manures. Vermicomposting research has been conducted in many countries worldwide (Edwards, 1998).

Animal manure generally makes suitable media for worm production. Swine manure can be an excellent medium for worm production; however, excess water must be separated
from the solid manure fraction in slurry or effluent prior to application of the worms. Since fresh swine manure may contain high concentrations of salts and ammonia, a period of composting or leaching may be required prior to the direct application of fresh swine manure to worm beds (Chan and Griffiths, 1988). Swine manure also may contain a relatively high concentration of trace metals that may have an adverse impact to the health of the earthworms (Edwards, 1998).

Fresh organic waste is frequently applied to the surface of the worm beds where the worms concentrate (upper 15-cm layer) to consume the fresh material. As the fresh organic material is consumed and processed, the worms continue to move to the surface as fresh material is added. The addition of fresh material must be carefully accomplished to maintain aerobic conditions by avoiding excessive moisture, prevent heating that occurs with composting, and reduce ammonia and salt accumulation. Clearly, considerable skill and expertise is required to optimize worm production and the processing of organic wastes.

Following vermicomposting, the worms are separated from the castings and returned to process additional organic material or sold directly. The manure solids are applied to worm beds that are maintained within an enclosed greenhouse facility (Riggle, 1997). After a period of processing, the final product is odor-free and has excellent physical properties for use as a plant growth medium. The vermicompost produced by this process is quite consistent throughout the year, since the composition of the manure does not change during the year and extreme environmental fluctuations are eliminated by the use of the greenhouse. Also, the use of vermicomposting for the treatment and processing of separated swine wastes solids has the potential of increasing the value of manure. The vermicompost has value as
a source of plant nutrients and as a plant-growth medium. Further investigation of the microbial transformations which occur during the vermicomposting period is needed to minimize the risk of pathogen transfer. Large scale production of vermicompost requires considerable skill, labor, and capital investment to be successful. Furthermore, this type of treatment only works with solid manures—not wastewaters. Therefore, careful planning should precede before undertaking a venture of this type (Mikkelsen, 1999).

**Aerobic Treatment of Swine Wastes**

Incorporating oxygen into liquid or slurry manure can promote aerobic biotreatment which is a less odorous process than anaerobic treatment. Continuous aerobic treatment for the purpose of odor control is affected by treatment time, temperature, dissolved oxygen level, and insulation factors. Aerobic treatment systems can be designed to meet defined odor control objectives (Miner, 1995).

Aerobic decomposition is effective in reducing odor-causing volatile acids and other odorous compounds (Swine Odor Task Force, 1995a). Aerobic lagoons require free oxygen to sustain aerobic bacteria which process wastes with less odor than anaerobic bacteria (Safely et al., 1993b; ASAE, 1994). Mechanical aeration of liquid manure in lagoons is an effective odor control method (Sweeten et al., 1991). Aeration rapidly reduces hydrogen sulfide emissions for swine manure. However, less volatile and less offensive compounds, such as phenols appear to persist (Sweeten et al., 1991). Aeration systems have been shown to reduce odor intensity and odor emissions by as much as 75% to 86% (Veenhuizen, 1996).

A properly designed and operated aerated lagoon will produce odors of lower
intensity and offensiveness, but these systems are relatively expensive to operate (Veenhuizen, 1996). The required oxygen concentration can be achieved by either designing the lagoon to be lightly loaded and shallow (maximum liquid depth of 5 feet) for maximum oxygen transfer or utilize a mechanical aerator (Safely et al., 1993b). Both types of lagoons require the separation of liquids and solids as a pretreatment step (Swine Odor Task Force, 1995b). Aerators should be sized to provide sufficient oxygen to minimize odor production potential and promote the decomposition of organic matter (Safely et al., 1993b).

The primary advantages of mechanically aerated lagoons over anaerobic lagoons are odor reduction, high treatment efficiency, and relatively small land area requirements (Sweeten, 1980). Mechanically, aerated lagoons are an alternative in highly populated areas or when there is a limited area available for manure storage. Mechanically aerated lagoons can be designed to standard lagoon depths and can meet defined objectives in terms of odor control (Miner, 1995). An oxygenation capacity sufficient to satisfy at least the five-day biochemical oxygen demand (BOD), plus the nitrogenous oxygen demand, is generally required (ASAE, 1994). In aerobic digesters, continuous aerobic culture treatment for controlling odor is affected by treatment time, temperature, dissolved oxygen level, and insulation factors (Miner, 1995).

Zhang et al., (1997) reports that since the anaerobic bacteria were responsible for producing nuisance odors in the anaerobic lagoon, surface aeration of the anaerobic lagoon forms an aerobic layer that may act as a blanket to suppress those odors. Within such a blanket, aerobic bacteria would convert odorous gases and organic compounds into odor-free gases before their release into the atmosphere.
A complete aerobic degradation of organic compounds can be expressed as:

\[
\text{Organic Compounds (C, H, O, N, S)} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{NH}_4^+ \text{ (or NO}_3^- + \text{S (or SO}_4^{2-}).
\]

Under aerobic conditions, the nitrogen compounds (proteins, peptides, amino acids and amines) are first converted into ammonium ions (\(\text{NH}_4^+\)) by heterotrophic bacteria and then converted into nitrite by autotrophic bacteria. Sulfur compounds (sulfur-containing aminoacids mercaptans, and sulfides) are converted into elemental sulfur (\(\text{S}\)) or sulfate (\(\text{SO}_4^{2-}\)) by sulfur-oxidizing bacteria. The emission of odor-causing nitrogen and sulfur compounds produced in the anaerobic environment is, therefore, prevented. The rate of aeration can maintain the dissolved oxygen (DO) in the surface liquid layer (about 30 cm deep) at 0.5 mg/L. Thus, the rate of aeration was effective in controlling odor emission from swine manure stored in laboratory-scale lagoons (Zhang et al., 1997).

**Study Objective and Scope**

Previous studies of the aerobic treatment of swine waste were performed at the lagoon and laboratory scale (Miner, 1995). Most studies relating to this type of treatment were conducted exclusively on surface aeration. The purpose of this study is to evaluate the effectiveness of the aerobic treatment of the underdrain where oxygen in the air is bubbled into the swine slurry by the use of diffusers. Besides adding oxygen to the underdrain, aerobic bacteria (activated sludge) were also added. The primary basis of this study is to regulate the underdrain wastewater’s chemistry by maintaining aerobic conditions and
introducing aerobic bacteria that can potentially expedite the treatment process. By altering the underdrain conditions as such, anaerobic reactions producing odorous compounds should be greatly reduced, if not eliminated. Under these controlled conditions, aerobic bacteria would be able to degrade the waste faster. This would result in a smaller lagoon and land required for storage and application. The scope of this study was to consider the effectiveness of various treatments at a pilot scale facility. Possibly, economic benefits could be realized from this proposed treatment process, although economic considerations are beyond the present scope of study.
Figure 2.1. Reaction scheme for anaerobic digestion

1. Fermentative Bacteria
   - Chemoheterotroph nonmethanogens
   - Acid-Forming Bacteria
2. Hydrogen-Producing Acetogenic Bacteria
3. Acetoclastic Methanogens
4. Carbon Dioxide-Reducing Methanogens

COMPLEX WASTE

Proteins
- Amino Acids

Carbohydrates
- Sugar

Lipids
- Fatty Acids
- Alcohols

Intermediate Products
- Propionic acid
- Butyric Acid
- Etc.

Acetate, Ammonia
and Hydrogen Sulfide

Hydrogen and Carbon Dioxide

Methane and Carbon Dioxide
### Table 2.1. Tested Pit Additives

<table>
<thead>
<tr>
<th>Trade name</th>
<th>Classification</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPC</td>
<td>Chemical emulsifier</td>
<td>Helps eliminate odor-causing bacteria</td>
</tr>
<tr>
<td>Bio-Safe</td>
<td>Enzymes and microorganisms</td>
<td>Stimulates bacteria to break down odor-generating compounds</td>
</tr>
<tr>
<td>Shac</td>
<td>Natural coal product (enzyme)</td>
<td>Enhances biological and chemical processes to reduce odor</td>
</tr>
<tr>
<td>X-Stink (LF1)</td>
<td>Aerobic bacteria</td>
<td>Breaks down volatile organic compounds</td>
</tr>
<tr>
<td>CPPD</td>
<td>Chemical oxidizing agent</td>
<td>Increases oxygen level in liquid to support bacterial activities</td>
</tr>
</tbody>
</table>
CHAPTER III

MATERIALS AND METHODS

Materials

Swine Raising Facility

This study was conducted in the Swine Physiology Barn of the Mississippi Agricultural and Forestry Experimental Station (MAFES) of Mississippi State University. It is located at the South Farm of Mississippi State University (approximately 1 ½ miles south of the campus). The overall dimension of the barn is 50' by 12'. The barn was equally partitioned into two 50' by 5' wastewater collection pits that were covered with 1/2” steel grating which allows waste to drop freely into the pit below. A 50' by 2' sidewalk ran along the middle of the barn; thus separating the two animal holding areas. The floor under the grating which supported the pigs was slanted and ranging from 2 feet at the shallow end to 5 feet at the deep end. Each pit was filled with water and had a wetted volume of approximately1,000 gallons. The layout of the facility is shown in Figure 3.1.

Animals

There was a total of 24 head at any given time contained within the barn. Twelve
head were located on each side of the barn. This operation closely resembles commercial swine raising facilities. The hogs were moved in as young juveniles and were weighed every three days and this weight was recorded. Figure 3.2 tracks their weight gain over time. Corn and soybean comprised their main diet.

**The Aeration System**

A blower system was installed to aerate the water within the underdrain via air sparging; thus, providing oxygen into the underdrain water. The blower system was comprised of a 1-hp (746-watt) regenerative blower, a flow meter, a series of valves, 2-in (5.1-cm) ID PVC process pipes, and twenty-eight 7-in (18-cm) ID ceramic diffusers (14 per pit). The aeration distribution network of this system was plumbed with the PVC pipe with 7-in diameter ceramic diffusers screwed onto the pipes at various distances. The aeration distribution system was mounted in parallel on the floor of the pit running from the deeper end to the shallow end. The blower, capable of generating 50 cfm (1.4 m³) of atmospheric air, was mounted on the outside of the barn so that the noise would not adversely effect the health of the animals. Air generated from the blower came through the flow meter and then to the aeration distribution network in the underdrain on both pits. Figure 3.3 is a schematic layout of the aeration system.

**Flux Chambers**

Because the barn was not completely sealed from the outside air and fans continuously were circulating air within the barn, flux chambers were designed and installed
to isolate small head spaces above the surface of the underdrain water so that it was not affected by drafts. This prevented the air phase composition from being diluted via mixing with the fresh air from the ambient and allowed for true air-phase concentration to be analyzed. The flux chambers were constructed from two 1-gallon and two 8-gallon buckets. One 8-gallon bucket was permanently located at the deep end, and one 1-gallon bucket was periodically moved randomly around the shallow end of each collecting pit. The cans were turned upside down and by merit of their dimensions were partially submerged in the underdrain water (see Figure 3.4). Holes were cut in the submerged part of the bucket so that the wastewater could circulate freely in and out. The portion of the can remaining above the waterline and exposed to the air was drilled with holes so that the air phases could be analyzed by portable meters. (Sampling tubes were inserted into trapped headspace via use of small sampling tubes).

**Sampling Strategy**

This research was conducted at the MSU Swine Physiology Barn. During this time, another research project was also underway. Both underdrain wastewater pits were not often available for a direct comparison between the control and the treated pits. Thus, only a few direct comparisons were available. For the rest of the time, the data were collected from one wastewater collection pit. The length of each testing period was seven days. The underdrain wastewater was emptied, and the collections pits were cleaned every Wednesday. Tap water was used to refill the pits on the same day after they were cleaned. The data were collected three to four times per each test period. A total of 28 runs were performed. Seven runs were
performed during the Fall of 1999 and 21 runs performed during the Spring of 2000.

A total of three systems were evaluated in this study. The first system was the control system in which the wastewater remained undisturbed in the pit mimicking current practices. The second system was the aerated (AER) system which the underdrain wastewater was sparged with atmospheric air at 50 cfm. The last system was the aerated and seeded (AERSE) system which is similar to the AER system, except that 10 gallons of activated sludge were used as seeds in each collection pit.

Wastewater samples were taken at Days 1, 5, and 7 of the testing cycle for all runs. Duplicate samples were collected from both the shallow and deep ends of the pits. Samples were collected in labeled 500-ml Nalgene bottles. One set of the samples was carried back to the MSU E-Tech Laboratory and the other to the ABE Water Quality Laboratory, and chemical analyses performed for various analytes at the two laboratories (different tests were performed at the two laboratories).

Air samples were taken at Days 1, 5, and 7 of the testing cycle. Two sampling locations were used at each pit. One was located at the fixed flux chamber located at the deeper end, and the other was located at the flux chamber that was randomly moved within the pit for each testing day. See Figure 3.1 for a schematic of sampling locations.

The theoretical COD load calculated for testing cycles ranged from about 15 lbs COD/7days (d) to 110 lbs COD/7d. For comparison purposes, the testing cycles for each system were divided into three groups based on COD load. The first group was considered a low-range load with COD loads ranging from 0-36 lbs COD/7d. The next group was a mid-range load with COD loads ranging from 37-72 lbs COD/7d. The last group was a high-
range load with COD loads ranging from 73-110 lbs COD/7d. The data obtained from testing cycles that fell into a respective group were averaged into a single value for each day within a testing cycle. This allowed for direct comparison among the systems within the three loading ranges.

Tables C.1 - C.3 in Appendix C list the estimated COD loads and dates for each test cycle. The control system was evaluated 12 times. Two control testing cycles were tested in the low range (Table C.4), five in the mid-range (Table C.5), and five in the high-range (Table C.6). The AER system was tested 10 times. Two aeration testing cycles were conducted in a low range (Table C.7), five in the mid range (Table C.8), and three in the high range (Table C.9). Lastly, the AERSE system was tested six times. Two AERSE testing cycles were run in the low range (Table C.10), three in the mid range (Table C.11), and one in the high range (Table C.12).

Seeds

Aerobic degradation of animal waste does not result in the formation of odorous volatile compounds. The aerobic bacteria that are well known for this activity are used extensively in Municipal Wastewater Treatment Plants. They provide a shorter treatment time compared to the anaerobic treatment. The aerobic bacteria that was used to seed the underdrain water, BOD, and the respirometer was obtained from the Starkville Municipal Wastewater Treatment Plant (an Activated Sludge Plant).
Respirometric Experiments

According to Greenberg et al. (1999) Method 5210 D, respirometric methods are useful for assessing the oxygen requirement for essentially complete oxidation of biologically oxidizable matter and the need for using adapted seed in other biochemical oxygen-uptake measurements, such as the dilution BOD test; and stability of sludge.

A BI-1000 Electrolytic Respirometer was used to measure the oxygen uptake rate (OUR) exerted by the aerobic microbes in the samples. This instrument is designed to measure the oxygen uptake in samples that are contained in sealed flasks. This device also may be used to estimate a continuous BOD. Within the electrolytic cell, oxygen pressure over the sample is held constant by continually replenishing the oxygen used by the microorganisms. Oxygen replacement was accomplished by means of an electrolysis reaction in which oxygen was produced in response to changes in the head-space pressure. The OUR readings were determined by the length of time that the oxygen was being generated and correlating it to the amount of oxygen generated by the electrolysis reaction (Metcalf and Eddy, 1991).

The respirometric experiments were periodically undertaken using samples collected from the underdrains and run at the MSU E-Tech Laboratory. A total of eight flasks was used for each experiment. Two flasks were filled with distilled water which served as water controls. Another two flasks were seeded with 30 ml of activated sludge and served as sludge controls. The sludge control was used to monitor cell decay that contributes to the
OUR measurement. Another two flasks were filled with 100 ml of wastewater samples without seeds. The last two flasks were filled with 100 ml of wastewater sample and 30 ml of activated sludge. Then, all eight flasks were diluted with distilled water and 10 ml of concentrated stock nutrient solution used to make up the total volume of 1000 ml per flask. The composition of the fully diluted nutrient solution was: 800 mg/L NaH$_2$PO$_4$, 260 mg/L of NH$_4$Cl, 170 mg/L MgSO$_4$, and 60 mg/L FeCl$_3$.

**Wastewater Analysis**

The following tests were performed on the samples collected from the pits: biochemical oxygen demand (BOD), chemical oxygen demand (COD), dissolved oxygen (DO), total solid (TS), pH, redox potential (ORP), ammonia (NH$_3$-N), ortho-phosphate (PO$_4^{3-}$-P), phenol, nitrate, alkalinity, and volatile acids (VA). DO and ORP were measured directly from both the shallow and the deep ends of the pits. NH$_3$-N, pH, COD, and PO$_4^{3-}$-P were analyzed by the ABE Water Quality Laboratory. BOD, TS, phenol, nitrate, alkalinity, and volatile acids were run by the MSU E-Tech Laboratory. Table 3.1 describes the instrumentation protocol used by both laboratories.

**Gas Analysis**

The headspace above the pit was analyzed for various gas constituents. A GasTech Portable Gas Monitor RS-232 was used for analyzing O$_2$, CO$_2$, and volatile organic compounds. A small peristaltic pump on the GasTech Portable Gas Monitor RS-232 draws air into the gas-sensing chamber. The gas sensor reads the air phase concentration of the
three gases, with oxygen and carbon dioxide read in percentages and volatile organic compounds read in parts per million (ppm). The Drager Accuro ARMF-F015 tube system was used for analyzing volatile acids, mercaptans, phenols, ammonia, hydrogen sulfide, and methane. A mechanical pump of the Drager Accuro ARMF-FO15 draws air through the testing tubes that specifically make for testing individual compound. The tubes are packed with a chemical that will colorimetrically react with a specific compound in the air yielding a concentration range of 0.25-50 ppm. Measurements were taken by inserting the intake tube of the meter or the packed tubes of the Drager Unit through the holes of the flux chamber directly above the surface water. The tubes were placed as close to the water surface as possible without drawing water into the tubes.

**Odor Panel**

A human odor panel was established for the study. The panel was comprised of 10-15 volunteers from various departments at Mississippi State University (MSU). The panel was approved by the Institutional Review Board (IRB #00-075) of MSU for human testing. The panel trained three times per week for about 2 months. During these weekly meetings, various swine wastewater samples were introduced to the odor panel. Nine descriptive terms were chosen to describe the odor. They were overall intensity, acridity, ammonia, cheesy, earthy, sweet/grainy, musty, sulfurous, and fecal. Each term was rated on a 0-8 point scale, where, 0 represents no detectable odor and 8 represents a strong odor. The standard that was prepared from a mixture of p-cresol (210 mg/L) and skatole (12.8 mg/L) in deionized water was assigned a rating of 4 for both overall odor intensity and fecal
characteristic. All odor samples were rated against this standard. Furthermore, the samples were rated as being pleasant at 0, neither pleasant nor unpleasant at 4, and a very unpleasant odor at 8 of the 0-8 point scale.

Samples were collected in the 250 mL Nalgene Teflon FEP One-Piece Wash Bottles and were evaluated within 6 hours of collection. These bottles were selected because of their high resistance to adsorption/absorption of liquids or gases. The internal drawtube was removed from each bottle to keep the liquid portion of the sample from escaping into the neck. The bottles were covered with aluminum foil and randomly numbered. A small piece of glass wool was plugged into the neck of the stem every time the bottles were used. Only 8-10 samples were analyzed for each meeting to reduce the effect of olfactory dulling. The bottles were washed with soap and water, rinsed thoroughly, and placed in a 100°C oven overnight to make sure they are odor free for the next sampling and subsequent testing by the odor panel.

To analyze a sample, the panelist swirled the bottle so that the odorants were filled the bottle head-space. Then, gently squeezed the bottle in a series of pulses to force the odorant laden atmosphere out of the bottle into an area between the nose and the lip. The panelist was not allowed to touch the stem with any part of his/her face. The score was recorded on the score sheet by each panelist according to his/her response to the odorant.
Figure 3.1. Swine raising facility
Figure 3.2. Hog's weight vs. time
Figure 3.3. The aeration system
Figure 3.4. Flux chamber
Table 3.1. Wastewater analysis instrumentation and protocol

<table>
<thead>
<tr>
<th>Analylate</th>
<th>Instrument</th>
<th>Protocol</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOD</td>
<td>YSI52 - Dissolve Oxygen meter w/ probe; 500-ml Wheater BOD Bottles</td>
<td>Procedure 5210B, Standard Methods</td>
</tr>
<tr>
<td>COD</td>
<td>Hach COD Reactor (Model 45600) and Hach DR/4000 Spectrophotometer</td>
<td>¹Hach Method #8000 Reactor Digestion Method High Range (0-1500 ppm) Vials</td>
</tr>
<tr>
<td>TS</td>
<td>Precision Scientific Model 144 Drying Oven (105°C)</td>
<td>Procedure 2540B Standard Methods</td>
</tr>
<tr>
<td>DO</td>
<td>Hach Sension6 - Dissolved Oxygen Meter w/ probe</td>
<td>Procedure 4500-O Standard Methods</td>
</tr>
<tr>
<td>pH</td>
<td>Orion SensorLink pH/ISE/ORP</td>
<td>Procedure 2510B, Standard Methods</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>Accument/Fisher Scientific AR25 - pH meter</td>
<td>Procedure 2320B, Standard Methods</td>
</tr>
<tr>
<td>NH₃-N</td>
<td>Hach DR/4000 Spectrophotometer</td>
<td>¹Hach Method #8048 Ascorbic Acid Method Phos Ver 3 Powder Pillow</td>
</tr>
<tr>
<td>Nitrate</td>
<td>Accument/Fisher Scientific AP62 Meter</td>
<td>Direct sensing platinum electrode combined with Ag/AgCl reference electrode</td>
</tr>
<tr>
<td>ORP</td>
<td>Hack Sens Ion2 - pH, ISE Meter, Sension Combination ORP Electrode Model #50230</td>
<td>Direct sensing platinum electrode combined with Ag/AgCl reference electrode</td>
</tr>
<tr>
<td>PO₄³⁻P</td>
<td>Hach DR/4000 Spectrophotometer</td>
<td>¹Hach Method #8048</td>
</tr>
<tr>
<td>Phenols</td>
<td>Hach DR/4000 Spectrophotometer</td>
<td>¹Hach Method #8047 4-Aminoantipyrine Method</td>
</tr>
<tr>
<td>VA</td>
<td>Hach DR/4000 Spectrophotometer</td>
<td>¹Hach Method #8196 Esterification Method</td>
</tr>
</tbody>
</table>

¹. Hach DR/2010 Spectrophotometer Manual
². Greenberg et al. (1999)
CHAPTER IV

RESULTS AND DISCUSSION

This chapter presents the relationship between the controls and the aerated (AER) and aerated with seed (AERSE) systems for each of the loading ranges. Having an access to only one wastewater collection pit, a direct comparison among the systems could not be obtained. Due to the changes in waste loads from week to week, a normalization technique of COD and BOD were devised to better elucidate the comparisons between and among the systems. The normalization values are expressed in $C/C_{est}$, whereas, $C$ is the actual concentration that was measured in the pits and $C_{est}$ is the theoretical value that is calculated based on the approximate hog’s weight and the pounds of COD and BOD they produced if no reduction occurs. According to the Agricultural Waste Management Field Handbook (1994), for every 1000 lb (454 kg) of pig weight, there are 6.06 lb COD and 2.08 lb BOD produced. Assuming a linear growth rate, pig weight can be approximated at any given time, and the organic waste load entering the collecting pit calculated. Note that the feed entering the collecting pits would also contribute to the COD and BOD and were not take into consideration when the theoretical values were calculated.
Respirometric Results

In this experiment, swine waste samples that were collected from the underdrain from the South Farm were tested using the respirometry test. The results are shown on Figures 4.1, 4.2, and 4.3. Figure 4.1 presents the results of a run prepared at the end of the second week after the juvenile hogs were moved in and the waste was allowed to accumulate for one week. This figure clearly shows that the sample seeded with 30-ml of activated sludge used more oxygen compared to other runs starting at 15 hours. This finding indicates that the seeded aerobes adjusted quickly to the wastewater. For the run using sample alone, little oxygen utilization occurred indicating that few aerobes were present. As expected, the water control did not consume oxygen. It was surprising that the activated sludge control, which is the seed control, used little oxygen. This indicates a fairly mature sludge with little free substrate remaining.

Figure 4.2 presents the results of a run prepared at the end of the Week Four after the hogs had moved in and wastewater was allowed to accumulate for a week. The differences between these runs are very striking. The sample seeded with activated sludge had the highest oxygen uptake, followed by the sample without activated sludge seeding. Activated sludge and water controls followed in a descending order, respectively. A similar trend is noted with Figure 4.3. The method of collecting samples used in Figure 4.3 were the same as those used within Figure 4.1 and Figure 4.2 data, except that the samples used in Figure 4.3 were collected at the end of the seventh week.

The accumulative oxygen consumed (exhibited in Figure 4.1) is considerably less than that shown in Figure 4.2 which is less than the data in Figure 4.3. The reason for these
differences is that as the hogs grew, they produced more waste. The accumulative oxygen consumed is directly proportional to the amount of biodegradable waste, and the amount of waste produced is directly related to the total body weight of the hogs. So in Figure 4.1, the hogs were young, and the amount of waste that was produced was minimal. As they grew, they generated more waste. Because of that, there is an increase in accumulative oxygen consumed from Figure 4.1 to Figure 4.3.

In these respirometric studies, the sample that was seeded with activated sludge had a higher rate of oxygen consumption compared to the sample without seeds. The rate of oxygen consumption is directly related to the rate of degradation of waste products. The faster the waste is degraded, the shorter amount of time required for treatment. The fact that the sample without seed was taking up oxygen implies that there were facultative anaerobes in the waste. This indicates the presence of facultative anaerobic microorganisms. In conclusion, swine waste can be degraded faster in the presence of oxygen with its native microorganisms than in the absence of oxygen. Furthermore, this degradation process can be enhanced substantially if the sample was seeded with activated sludge, which contain optimal consortia of microorganism for degradation of wastes under aerobic conditions.

**Water Quality Results**

The raw water quality results for each test run with the control, AER, and AERSE systems are tabulated in Tables D.1 - D.28 of Appendix D. The average water quality results of the low-, mid-, and high-range loads of all the systems are tabulated in Tables E.1 - E3 of the Appendix E. For discussion purposes, the average water quality results are represented
as summary figures in this chapter. Each of the figures contain three plots representing the average result of each type of treatment (Control, AER, and AERSE).

For a given loading range, the controls were typically performed during Week One, AER in Week Two, and AERSE in Week Four. The number of hogs was held constant and their weight increased with time. So the waste load on the AERSE System should be higher than the waste load for the Control System at any given day of the testing cycle for each given loading range.

**Dissolved Oxygen**

Figures 4.4, 4.5, and 4.6 present the dissolved oxygen of the low-range, mid-range, and high-range testing cycles, respectively. Fresh water that had a [DO] of approximately 4 mg/L was used to fill the underdrain pit at the beginning of every cycle. When the dissolved oxygen concentration within a biologically active system drops below 0.5 mg/L, it is generally considered that the system is devoid of oxygen and below acceptable levels to sustain aerobic activity. The controls for all three ranges had the [DO] fall below 0.5 mg/L on Day 1 and remained at this level throughout the testing cycle. In other words, the controls were essentially anaerobic after Day 1. In Figure 4.4, the AER and AERSE systems for the low-range load runs appear to maintain aerobic conditions within the underdrain wastewater throughout the week. In Figure 4.5, for the mid-range load runs, only the AER system remained aerobic throughout the week, whereas the AERSE system became anaerobic on Day 1. This finding indicates that the additional bacteria increase the oxygen demand of the system. In Figure 4.6, all of the high-range load systems became anaerobic after Day 2.
These data suggest that aerating the pit does have potential for sustaining aerobic conditions for the low-range and mid-range loadings; however, neither of the systems were effective in maintaining appreciable DO under high loading rates.

**Nitrate**

Nitrate is derived from the oxidation of NH$_3$ by a bacterial-based process known as nitrification. Two bacterial genera are responsible for nitrification, *Nitrococcus* and *Nitrobacter*. Nitrate is highly oxidized and usually the most abundant form of nitrogen in wastewaters from bio-processes (Metcalf & Eddy, 1991). Figures 4.7 through 4.9 present the nitrate concentrations versus time for low-range load, mid-range load, and high-range load, respectively. Within all three loadings, the control treatments had considerably higher nitrate concentrations compared to other treatments of their corresponding loading range (starting from Day 2 and continuing until the end of the cycle). Even though dissolved oxygen was depleted after Day 1 for the control treatment within all of these systems, it is speculated that nitrate can continue to form through the use of oxygen from the gas-liquid interface. On the other hand, when aeration and an activated sludge seed were applied, less nitrate was being formed. It’s believed that since the underdrains were aerated and seeded, the initial aerobic activity resulted in a high demand for nitrogen (NH$_3$) for cell synthesis. By Day 5, the waste load had accumulated and put a greater stress on the dissolved oxygen levels causing it to decrease. At this point, the aerobic bacteria began to use nitrate as a terminal electron acceptor. So as oxygen became low on Day 5, nitrate uptake increased. Thus, nitrate remained low for the AER and AERSE system due to both cell synthesis and
respiration associated with the higher bacterial population that aerating and seeding provide.

**Oxidation/Reduction Potential (ORP)**

According to Baker and Herson (1994), depletion of oxygen due to high loading of organic compounds causes ORP to drop. The ability of the different types of microorganisms to function is dependent on ORP level. For instance, aerobic and facultative anaerobic microorganisms require a minimal ORP level of +50 mV. Whereas, obligate anaerobic microorganisms require an ORP level around -200 mV as an optimum. Furthermore, during the biotreatment of organic wastes, the ORP level must be maintained above -200 mV to prevent malodor formation from occurring (Evans et al., 1986).

The tap water that was used to fill the pits at the beginning of the testing cycles had an ORP reading around 245 mV. For the low-range loads (Figure 4.10), the ORP of the control decreased rapidly to -200 mV by Day 5, with the AER system remaining at relatively high values throughout testing. In fact, the ORP of the AERSE system remained above 100 mV up to Day 5, thus favoring the activity of the aerobic and facultative anaerobic microorganisms. For the remainder of the testing cycle, the ORP of the AERSE system was above 0 mV. For the AER system of this range, the ORP level did not drop below -120 mV. Thus, according to Evans et al. (1986), malodor formation was likely reduced.

For the mid-range loads (Figure 4.11), the ORP of the control decreased to -300 mV by Day 2 and remained there for the rest of the test period. For the other two systems of this loading range, the ORP was dropped to around -200 mV by Day 2, which favors the activity of the obligate anaerobic microorganism. For the rest of the testing cycle, the ORP levels of
the aerated systems remained below -200 mV, indicating predominantly anaerobic activity. Clearly, this loading exceeds the oxygen capacity of the system.

For some reason, ORPs of the high-range loads (Figure 4.12) were not lower than the mid-range load, even though the dissolved oxygen of mid-range load was higher than the high-range load. At Day 2, the ORP was -100 mV for the AER system, -220 mV for the AERSE system, and -280 mV for the control system. The ORPs of the AERSE and the control systems leveled off after Day 2 to the end of the cycle. On the other hand, the ORPs for the AER continued to decrease after Day 2 to around -320 mV on Day 7. Nevertheless, low ORP levels correspond well to the high ammonia and volatile acids concentrations of the respective systems. These result will be discussed later in this chapter.

pH

Figures 4.13 - 4.15 present the pH values for the low-range, mid-range, and high-range loads, respectively. The tap water that was used to fill the pit at the beginning of the testing cycle had a pH value around 7.2. For the control system of all three loading ranges, the pH value was decreased steadily throughout the testing cycles to as low as 7.0 for the low-range load, 6.8 for the mid-range load, and 6.5 for the high-range load. These decreasing pH values reflect the increasing levels of volatile acids and ammonia which, according to Georgakakis et al. (1982), are the primary species controlling of pH (this will be discussed later in this chapter). For the AER and AERSE systems, the pH values increased with time corresponding to the low concentrations of volatile acids compared to the control of the respective loading range. However, ammonia concentration tended to
increase with time for the low-range and mid-range loads of these two treatment systems. These discrepancies will be explained later in this chapter when ammonia is discussed.

**Volatile Acids (VAs)**

Volatile acids are mainly comprised of acetic, propionic, butyric, and *iso*-butyric acids (Zhu and Jacobson, 1999). The VAs are produced from the deamination of amino acids that are produced during the processes of protein degradation and breakdown of carbohydrates. At a neutral pH, deamination is the major route for metabolism of amino acids. The bacterial genera involved in this activity usually include *Eubacterium, Peptostreptococcus, Bacteroides, Streptococcus, Escherichia, Megasphaera, Propionibacterium, Lactobacillus*, and *Clostridium* (Zhu and Jacobson, 1999). According to Mackie (1994), volatile acid is one of the odorous compounds in swine manure.

Figures 4.16 through 4.18 track volatile acid concentrations for the low-range, mid-range, high-range loads, respectively. For the controls of all three loading ranges, the volatile acid concentration increased throughout the testing cycle. In Figure 4.16, there is a remarkable difference between the control and the two other treatment systems. The concentration of volatile acids in the control system increased over time, whereas the concentrations in the other two systems were not readily changed throughout testing. The increase in volatile acid concentration of the control system corresponded to the decrease in pH (Figure 4.13). In the mid-range loads (Figure 4.17), volatile acids increased for all systems. There was a large increase in volatile acid concentration from Day 5 to Day 7 for the AERSE system; however, the corresponding pH did not change (see Figure 4.14).
Similarly, the pH of the AER system was not decreased as much as the control system, even though the volatile acid concentrations for both systems were increasing. The reason for a large increase in volatile acid concentration in the AERSE system is that this system was overloaded with wastes by Day 5, and aeration was no longer keeping up with the oxygen required for aerobic activities (see Figure 4.17). Additionally, it is important to remember that the AERSE systems had the higher waste loading compared to other two systems for the same loading range. So it is not surprising to see a large increase in volatile acids concentration after Day 2 for the high-range load and after Day 5 for the low- and mid-range loads.

For the high-range loaded tests (Figure 4.18), the volatile acid concentration for the control system were the highest at any given day, next to the highest was the aeration system, with the lowest being the AERSE system. Aerating the pit in this loading range did not maintain aerobic conditions within the pit, but it did keep the volatile acid concentrations low and keep the pH from changing as much as was observed with the control system.

**Phenols**

Phenolic compounds are present in freshly secreted manure (Spoelstra, 1977). They also are produced and accumulated in the storage systems where the mixture of feces and urine is decomposed by bacteria under the prevailing anaerobic conditions (Mackie, 1994). Zhu and Jacobson (1999) considered phenols as one of the major odorous compounds in swine manure. Phenolic compounds are biodegradable under anaerobic conditions (Ishaque et al., 1985) as well as under aerobic conditions (Fuchs, 1994). However, they continue to
accumulate with the increase in waste load overtime. This fact explains the observation for the control run for the three loading ranges (Figures 4.19, 4.20, and 4.21). These data show that phenol concentrations detected in the control runs constantly increased with time; whereas the treatments did not show that increasing pattern. This occurred because the control runs were anaerobic for almost all of the testing times. Similarly, for the high-range load (Figure 4.21), where dissolved oxygen was depleted by Day 1 or Day 2, the phenol concentrations detected in the AER and AERSE runs also increased. The AERSE phenol levels increased faster than those in the control because there was a higher waste load in the AERSE at any given time during the testing cycle for these two runs compared to the control. For the low-range loads (Figure 4.19), when dissolved oxygen adequately maintained aerobic conditions, the phenol concentrations for the AER and AERSE runs was considerably lower than those observed in the controls, even though the waste load for controls was less than the waste load of the other two runs. The same pattern can be seen with mid-range loaded runs up to Day 5 (Figure 4.20). After Day 5, there was a large increase in phenol concentration observed for the AER runs. It is believed that the cause of this increase is that the system had reached the point of overload at Day 5 in terms of phenol degradation, even though oxygen in high enough concentration to adequately provided aerobic conditions in the pit. However, the phenol concentrations of the AER and AERSE runs had much lower phenol concentrations than the control runs throughout the testing in spite of having higher waste loads.

The AER and AERSE systems seemed to be effective in controlling the phenols during the low-range and mid-range loads. However, they achieved relatively poor phenolics
control during high-range loads (Figure 4.21). The greater waste load of the high-range load had quickly exhausted the dissolved oxygen in the pit and was converted into an anaerobic environment which provided limited degradation of phenols (Ishaque et al., 1985). Figure 4.48 further emphasizes the fact that phenol removal greatly depended on the dissolved oxygen concentration. When the dissolved oxygen level dropped below 0.5 mg/L, phenol concentration sharply increased. In conclusion, phenol removal was more effective in aerobic conditions than in anaerobic conditions.

**Biochemical Oxygen Demand (BOD)**

According to Standard Methods by Greenberg et al. (1999), biochemical oxygen demand (BOD) is an empirical test composed of standardized laboratory procedures that are used to determine the relative oxygen requirements for organics biodegradation within wastewaters. The test is widely used to measure waste loads and to evaluate the pollutant removal efficiency of treatment systems. The test actually measures the amount of molecular oxygen utilized during a specified incubation period of biochemical degradation of organic material. In this experiment, the 5-Day Biochemical Oxygen Demand (BOD$_5$) test was used to evaluate the BOD-removal efficiency achieved by the various systems.

The BOD data are presented as normalized BOD versus time (Figures 4.22, 4.23, and 4.24) and as actual BOD concentration versus time (Figures 4.25, 4.26, and 4.27). The disadvantage of presenting the actual BOD concentration versus time is that the time difference between runs is ranging from one to four weeks within a loading range. During that time, the hogs increased in size; thus, producing more and more BOD load into the
underdrain as time went by. In other words, the BOD load of the AERSE system in Week 4 was higher than the load for the AER system was in Week 2, which, in turn, is higher than the control system performed in Week 1 for a given loading range. Even if BOD removal efficiency is higher in the AERSE and aeration systems compared to the control system, the BOD that was left unremoved was still higher than the BOD of the control system because there was a higher BOD load in these two systems at the beginning. So the BOD concentration versus time are expected to increase with time and be highest in the AERSE system and lowest in the control system.

As mentioned earlier in this chapter, the BOD data have been normalized to better compare the treatment systems. Figures 4.22, 4.23, and 4.24 represent the results of the normalized-BOD data of the low-range, mid-range, and high-range loads, respectively. There was a decreasing trend of normalized BOD starting from Day 1 for the AER system of the low-range load (Figure 4.22) and starting from Day 2 for the AER and AERSE systems of the high-range load (Figure 4.24). Even though there existed a decreasing trend in normalized BOD as described above, the controls were more effective in removing the BOD and maintaining it at a relatively low concentration compared to the AER and AERSE systems. However, there was an increasing trend of normalized BOD for all systems of the mid-range load. The evidence did not show an appreciable BOD-removal for the mid-range load (Figure 4.23). Under an anaerobic condition, BOD removal does occur (for example anaerobic lagoon), but it is much slower than aerobic treatment (Metcalf and Eddy, 1991).

Chemical Oxygen Demand (COD)
COD is a test that measures the equivalent quantity of oxygen utilized during the chemical oxidation of organic and inorganic matter in wastewaters. The oxygen equivalent of the organic matter that can be oxidized is measured by using a strong chemical oxidizing agent (potassium permanganate) in an acidic medium. Generally, the COD of a waste is higher than the BOD because more compounds can be degraded chemically than can be degraded biologically within the constraint of the tests. This test is useful because its results can be obtained within three hours; whereas it takes five days to run a BOD test (Metcalf and Eddy, 1991).

The COD data are presented as COD concentration versus time and normalized COD versus time (Figures 4.28, through 4.33). The COD concentrations increased with time for all testing cycles (Figures 4.28-4.30). As expected, the extent of increase was lower with the low-range load (Figure 4.28) than the higher loads (Figure 4.30) because the low-range load carried a smaller waste load than higher loads. For the low-range load (Figure 4.28), the COD concentrations increased steadily throughout the testing cycle for all three systems. Even though COD concentrations were increased with time, COD-removal could still take place because the COD input was exceeded the COD removal. Thus, the COD accumulation resulted in a steady increase in COD concentration. These results suggested that there was no difference in COD removal among the two treatments and the control because the COD concentrations increased at about the same rate for all systems.

For the mid-range load (Figure 4.29), only AER treatment appeared to perform better than control in COD removal. However, the COD concentration of the AERSE treatment still remained higher than the control throughout testing cycle. That did not necessarily mean
that there was no treatment taking place in the AERSE system because this system carried a higher waste load in the beginning. For the high-range load (Figure 4.30), the COD concentrations for the AER and AERSE were less than the COD concentrations associated with the control. In other words, AER and AERSE provided greater COD removal than those observed with the control.

The COD data shown in Figures 4.28, 4.29, and 4.30 have been normalized and these calculations are plotted in Figures 4.31, 4.32, and 4.33, respectively. Figures 4.31 represents the normalized COD data of the low-range load. In this loading range, there was a decrease in normalized COD of the AER and AERSE systems starting from Day 1 to the end of the testing cycle and a decrease in normalized COD of the control from Day 1 to Day 5. This decreasing trend suggested that the amount of COD removal exceeded the amount of COD input. However, there was an increase in normalized COD of the control from Day 5 to Day 7. It is speculated that after Day 5, the control system was overloaded, and the amount of COD removal of the control system was no longer able to keep up the amount of COD input. Thus, there existed an increasing trend from Day 5 to Day 7. However, this pattern did not exist in the normalized COD plots of the mid-range load (Figure 4.32) and high-range load (Figure 4.33) of the controls.

For the mid-range load (Figure 4.32) and high-range load (Figure 4.33), the normalized COD of all systems remained somewhat constant after Day 1. These results suggested that the amount of COD removal matched the amount of COD input. All systems at these ranges had about the same benefit in terms of COD removal.
Ammonia formation is the result of microbial degradation of urea in the urine and nitrogen compounds (proteins, peptides, amino acids and amines) in the feces (Zhang and Day, 1996). During anaerobic digestion, organic nitrogen compounds are transformed to ammonia nitrogen (Sanchez et al., 1995). Thus, wastewater from anaerobic pits contain high concentrations of ammoniacal nitrogen (Sanchez, 1980). Under aerobic conditions, the nitrogen compounds are converted into ammonium ions ($\text{NH}_4^+$) by heterotrophic bacteria and then into nitrite and nitrate by autotrophic bacteria ($\text{Nitrococcus}$ and $\text{Nitrobacter}$). This process is called nitrification (Zhang et al., 1997; Metcalf and Eddy, 1991). Furthermore, ammonial nitrogen can be removed from wastewater by heterotrophic bacteria (both anaerobic and aerobic) which assimilate ammonia nitrogen into cell mass as a nutrient source (Metcalf and Eddy, 1991).

Free ammonia concentrations within a wastewater depends primarily on the total ammonia concentrations, temperature, pH, and ORP (Hansen et al., 1997). Free ammonia concentrations increase with increasing temperature and pH (Koster, 1986). An increase in pH from 7 to 8 will actually lead to an eight-fold increase of the free ammonia concentration (Hansen et al., 1997).

Figures 4.34, 4.35, and 4.36 present the ammonia data versus time for the low-range load, mid-range load, and high-range load, respectively. In general, the ammonia concentration for all runs increased with time, except for the AERSE system of the high-range load, which began to decrease over Days 2 and 7. The reason for this decrease is not fully understood because the pH remained within the range of the other runs (pH~7.5)
throughout the testing period.

In the low-range load (Figure 4.34), ammonia concentration increased based on actual load; whereas, in the mid-range load (Figure 4.35), there was some benefit in reducing ammonia with the AER system. However, in the high-range load, AERSE system was beneficial to ammonia reduction. For the most part, ammonia concentrations generally follow the trends exhibited by the pH and the total solids data (See Figures 4.13-4.15 and 4.43-4.45).

Since the pH did not greatly change throughout a given cycle, it cannot be fully accounted for the increase in ammonia concentrations. When the ammonia concentration was plotted versus ORP (see Figure 4.49), the results clearly show that when ORP dropped below -200 mV, (which is anaerobic), the ammonia concentration increased much faster than those above -200 mV. Thus, high ammonia concentrations appear to result from high waste loads, low ORP as well as high pH.

**Alkalinity**

By definition, alkalinity refers to the capability of water to neutralize acid. It is an expression of buffering capacity. A buffer is a solution to which an acid can be added without changing the pH appreciably. Alkalinity in wastewater results from the presence of the hydroxides, carbonates, and bicarbonates. Wastewater is normally alkaline, receiving its alkalinity from the water supply (Metcaff and Eddy, 1991). The alkalinity in tap water is mainly comprised of calcium carbonate that was used during the water treatment to neutralized chlorine. The tap water that were used to fill the pits has an alkalinity
concentration of 78 mg/L.

When oxygen is present, nitrification is taking place. Because nitrifying bacteria that are responsible for nitrification are strict autotrophs, they are distinctly different from the heterotrophic bacteria responsible for the degradation of the organic matter (Metcalf and eddy, 1991). These microbial activities cause a drop in pH by neutralizing the alkalinity, thus lowering its concentration. Figure 4.38 shows the alkalinity concentration of the AER system. The alkalinity concentration was lower than the alkalinity concentration of the AERSE system and decreased from Day 5 to Day 7. This pattern corresponded to the ammonia concentration of the AER system in Figure 4.35. The ammonia concentration was much lower than the ammonia concentration of the AERSE system of the same figure. It is speculated that, in the AER system of the mid-range load, nitrifying bacteria utilized ammonia causing the pH to drop (Figure 4.14); therefore, lowering alkalinity.

When the alkalinity concentration is not properly maintained, it will hinder the activity of the strict autotrophs (Metcalf and Eddy, 1991). In the low-range load (Figure 4.37), the alkalinity levels were low compared to the alkalinity levels of mid-range and high-range loads. According to Figure 4.34, ammonia concentrations increased with time. It is believed that ammonia was not utilized by nitrifying microbes due to low alkalinity levels (Figure 4.37), even though dissolved oxygen (Figure 4.4) was adequate to maintain aerobic conditions in the underdrain.

For the high-range load (Figure 4.39), dissolved oxygen (Figure 4.6) was not adequate to maintain aerobic conditions in the underdrain. Thus, no nitrification was taking place. Alkalinity concentration increased with time and waste loads.
Orthophosphate (PO₄³⁻)

Figure 4.40-4.42 present the phosphate concentrations versus time for the low-range, mid-range, and high-range loads, respectively. Phosphorus appears in wastewater as orthophosphate, polyphosphate (P₂O₇), and organically bound phosphorus. Microorganisms (both aerobes and anaerobes) utilize phosphorus during cell synthesis and energy transport (Metcalf and Eddy, 1991). For the low-range and high-range loads (Figures 4.40 and 4.42), the AER and AERSE had a relatively higher orthophosphate concentrations compared to the control for most of the times. On the other hand, the mid-range load (Figure 4.41) shows that the AER and AERSE had a relatively lower orthophosphate concentrations compared to the orthophosphate concentration detected in the controls at times. At this loading range, aerating the pits results in an increase in cell mass formation; thus, lowering the phosphate concentrations in the underdrain. However, this pattern could not be seen in the low-range load (Figure 4.40) or high-range load (Figure 4.42). Figures 4.40 and Figure 4.42 show that the orthophosphate concentration increased with an increase in waste load and time.

Total solids (TS)

Figures 4.43 through 4.45 present the total solids concentrations versus time for the low-range, mid-range, and high-range loads, respectively. The total solids concentration generally increased as the waste load and time increased. Aerating the pits caused aerobic growths resulting in a relatively higher biomass formation in the AER and AERSE compared to the control for the low-range load (Figure 4.43) and mid-range load (Figure 4.44).
Furthermore, AERSE exhibited a higher total solids concentrations compared to the AER. However, aerating the high-range load (Figure 4.45) did not show any aerobic growth because of the lack of oxygen to keep the underdrain aerobic at this loading range; thus, the total solids concentrations were about the same as the control.

Air Quality Results

The air directly above the pits were monitored for ammonia, hydrogen sulfide, oxygen, and carbon dioxide. The oxygen and carbon dioxide concentrations directly above the pits were identical to their concentrations in the open air. Hydrogen sulfide was monitored four days per testing cycle, but none was detected. Thus, oxygen, carbon dioxide, and hydrogen sulfide will not be discussed any further. On the other hand, ammonia was measured in Days 1, 2, 5, and 7 of each testing cycle. Only the data of the low-range load (Figure 4.46) and mid-range load (Figure 4.47) were obtained and will be discussed in this chapter. Furthermore, olfactory evaluation of the control and the AER systems of the high-range load (Table 4.1) and between the AER and AERSE systems of the low-range load (Table 4.2) were obtained and will be discussed in this chapter.

Ammonia

According to Henry’s law, when a volatile compound, such as ammonia, is dissolved in water, a small amount exists in gaseous form immediately above the surface of the water. In other words, there is an equilibrium between the liquid phase and the gas phase of ammonia immediately above the surface of the pit, and the concentrations of the two phases
are directly related (LaGrega et al., 1994). For any reversible reaction-formation system, the driving force of the equilibrium depends on the availability of the reactants and/or products, the pH, and the temperature. Since the temperature of the barn was relatively constant throughout the testing cycle, it should not greatly effect the equilibrium of the gas and liquid phases of ammonia.

As discussed earlier, the high pH and the high waste load resulted in a relatively high ammonia formation in the underdrain wastewater. Also, the AERSE system resulted in the highest ammonia concentration. Next to it was the AER system. Finally, the system that resulted in the lowest ammonia concentration was the control system for a given testing cycle. A similar trend is seen in the air phase ammonia which the concentrations are ranging from the highest to the lowest are the AERSE, AER, and control systems (Figures 4.46 and 4.47). The results showed that the ammonia concentration of the air phase is directly dependent on the ammonia concentration of the liquid phase. The higher the concentration of ammonia in the liquid phase, the higher is the concentration of ammonia in the gaseous phase.

It should be noted that aerating the pit could potentially strip the ammonia from the liquid phase into the air phase. Whether stripping had occurred or not, it is difficult to determine because the AER run and the control run did not carry the same waste loads.

**Olfactory Evaluation**

Mean odor responses for Day 7 for the high-range load and low-range load are tabulated in Table 4.1 and 4.2, respectively. The overall odor intensity is the highest odor
intensity, except for pleasantness response, and none of the other responses should be higher than the overall odor intensity. The earthy and musty odors is formed from the volatile metabolites during the normal Actinomycete development. The two compounds that were isolated and identified as the agents responsible for the earthy and musty odors by Csuros and Csuros (1999) are geosmin and 2-methylisoborneol. It also should be noted that the pleasantness response data were unavailable for the high-range load in Table 4.1.

In Table 4.1, all the responses for the control system, except the earthy and the sweet responses, are considerably higher than the AER system. Especially, the overall odor intensity of the control system was rated near the top of the scale (lowest at 0 and highest at 8) which is much higher than the AER system. The next highest response of the control system in this Table is the fecal response. Fecal response is considerably higher in the control system (an anaerobic treatment) compared to the AER system (an aerobic treatment). In Table 4.2, the overall odor intensity and the pleasantness responses are higher in the AER system than in the AERSE system. All other responses are very low on the scale (lowest at 0 and highest at 8) and are mixed. Based on the overall odor intensity, the control system resulted in the higher response than the AER system (Table 4.1), and the AER system resulted in higher response than the AERSE systems (Table 4.2). Therefore, it can be induced that the AERSE system provided the best treatment in controlling odor based on the overall odor intensity followed by the AER system and than the control system.
Figure 4.1. Respirometric Experiments on Swine Waste during Week 2
Figure 4.2. Respirometric Experiments on Swine Waste during Week 4
Figure 4.3. Respirometric Experiments on Swine Waste during Week 7
Figure 4.4. Dissolve oxygen vs. time for the low-range load

Figure 4.5. Dissolve oxygen vs. time for the mid-range load
Figure 4.6. Dissolve oxygen vs. time for the high-range load

Figure 4.7. Nitrate concentration vs. time of the low-range load
Figure 4.8. Nitrate concentration vs. time for the mid-range load

Figure 4.9. Nitrate concentration vs. time for the high-range load
Figure 4.10. ORP level vs. time for the low-range load

Figure 4.11. ORP level vs. time for the mid-range load
Figure 4.12. ORP level vs. time for the high-range load

Figure 4.13. pH vs. time for the low-range load.
Figure 4.14. pH vs. time for the mid-range load

Figure 4.15. pH vs. time for the high-range load
Figure 4.16. Volatile acids concentration vs. time for the low-range load

Figure 4.17. Volatile acids concentration vs. time for the mid-range load
Figure 4.18. Volatile acids concentration vs. time for the high-range load

Figure 4.19. Phenol concentration vs. time for the low-range load
Figure 4.20. Phenol concentration vs. time for the mid-range load

Figure 4.21. Phenol concentration vs. time for the high-range load
Figure 4.22. Normalized BOD vs. time for the low-range load

Figure 4.23. Normalized BOD vs. time for the mid-range load
Figure 4.24. Normalized BOD vs. time for the high-range load

Figure 4.25. BOD concentration vs. time for the low-range load
Figure 4.26. BOD concentration vs. time for the mid-range load

Figure 4.27. BOD concentration vs. time for the high-range load
Figure 4.28. COD concentration vs. time for the low-range load

Figure 4.29. COD concentration vs. time for the mid-range load
Figure 4.30. COD concentration vs. time for the high-range load

Figure 4.31. Normalized COD vs. time for the low-range load
Figure 4.32. Normalized COD vs. time for the mid-range load

Figure 4.33. Normalized COD vs. time for the high-range load
Figure 4.34. Ammonia concentration vs. time for the low-range load

Figure 4.35. Ammonia concentration vs. time for the mid-range load
Figure 4.36. Ammonia concentration vs. time for the high-range load

Figure 4.37. Alkalinity concentration vs. time for the low-range load
Figure 4.38. Alkalinity concentration vs. time for the mid-range load

Figure 4.39. Alkalinity concentration vs. time for the high-range load
Figure 4.40. Orthophosphate concentration vs. time for the low-range load

Figure 4.41. Orthophosphate concentration vs. time for the mid-range load
Figure 4.42. Orthophosphate concentration vs. time for the high-range load

Figure 4.43. Total solids concentration vs. time for the low-range load
Figure 4.44. Total solids concentration vs. time for the mid-range load

Figure 4.45. Total solids concentration vs. time for the high-range load
Figure 4.46. Air phase ammonia vs. time for the low-range load

Figure 4.47. Air phase ammonia vs. time for the mid-range load
Figure 4.48. Phenol concentration vs. dissolved oxygen concentration

Figure 4.49. Oxidation/reduction potential vs. ammonia concentration
Table 4.1. Average Odor Responses for Day 7 (High-Range Load)

<table>
<thead>
<tr>
<th>System</th>
<th>Overall Odor Intensity</th>
<th>Acridity</th>
<th>Sulfurous</th>
<th>Earthy</th>
<th>Musty</th>
<th>Fecal</th>
<th>Cheesy</th>
<th>Sweet</th>
<th>NH₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>7.49</td>
<td>1.41</td>
<td>2.39</td>
<td>0.19</td>
<td>1.55</td>
<td>4.50</td>
<td>2.60</td>
<td>0.38</td>
<td>0.91</td>
</tr>
<tr>
<td>AER</td>
<td>4.59</td>
<td>0.55</td>
<td>1.58</td>
<td>0.67</td>
<td>0.91</td>
<td>2.60</td>
<td>1.27</td>
<td>0.47</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Table 4.2. Average Odor Responses for Day 7 (Low-Range Load)

<table>
<thead>
<tr>
<th>System</th>
<th>Overall Odor Intensity</th>
<th>Acridity</th>
<th>Sulfurous</th>
<th>Earthy</th>
<th>Musty</th>
<th>Fecal</th>
<th>Cheesy</th>
<th>Sweet</th>
<th>NH₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>AER</td>
<td>2.89</td>
<td>0.37</td>
<td>0.39</td>
<td>0.94</td>
<td>0.78</td>
<td>0.96</td>
<td>0.56</td>
<td>0.31</td>
<td>0.21</td>
</tr>
<tr>
<td>AERSE</td>
<td>1.81</td>
<td>0.34</td>
<td>0.39</td>
<td>0.22</td>
<td>0.29</td>
<td>0.80</td>
<td>0.42</td>
<td>0.14</td>
<td>0.17</td>
</tr>
</tbody>
</table>
CHAPTER V

ENGINEERING SIGNIFICANCE

The economic impact of the swine industry is very significant to the States of Mississippi, North Carolina, and Iowa. There is no doubt that odor control in the swine industry needs to be improved to avoid negative public perceptions and litigation toward the swine industry. Although many technologies are available for swine waste treatment and odor reduction, they are not cost effective for swine producers. Thus, the need for other economically feasible alternatives is clear.

Based on the results presented in the previous chapter, either AER or AERSE systems may be viable alternative for swine wastewater management and odor control. Activated sludge is available at any City Municipal Wastewater Treatment Plant at no or minimal cost. A one-time cost for a generative pump and PVC pipes is needed to aerate the underdrain wastewater with atmospheric air. The other major cost is the cost of electricity to operate the generative pump. For 50 cfm of atmospheric air that was used to aerate the underdrain of this study, the underdrain maintained aerobic as long as the BOD was less then 10 lbs per day (112 lb O₂ per 1,600 lbs of hogs). When the BOD exceeded 10 lbs per day, the underdrain became anaerobic within two days. Those results can be seen from Day 5 to Day 7 of the mid-ranged load (Figure 4.5) and from Day 2 to Day 7 of the high-ranged load (Figure 4.6).
The aeration system that was used in this study did not provide adequate oxygen to maintain an aerobic environment in the underdrain at the high-range load. The underdrain pits in the barn were too shallow to allow effective oxygen transfer to occur. Possibly, a deeper pit or a more efficient aeration system is needed to maximize oxygen transfer in order to maintain an aerobic condition in the underdrain during the high-range load. Other aeration technologies that may be used are hydrogen peroxide, ozone, membrane diffusion, and pure oxygen. An alternative to either increased sizing of aeration equipment or the use of expensive liquid oxygen sources is increasing the rate of underdrain water exchange. This would reduce the net organic load on the set pit volumes; thus, potentially allowing an aeration system to more effectively maintain aerobic conditions.

The limitation of the swine-raising facility that was used in this study was that only one pit was available at a given time for the study, preventing a direct comparison among the treatment systems. A larger facility with more pits will allow the direct comparisons of more treatment systems. This would reduce variations in performance affected by environmental factors and wasteloads. The advantage of this swine facility is that it closely resembles large-scale swine production facilities.
CHAPTER VI

CONCLUSIONS

This research suggests that aeration and aeration plus seeding were beneficial to wastewater treatment and odor control when applied at low to moderate loadings. Specific conclusions from the research are listed below:

- The AER system maintained the DO concentration in the underdrains above 0.5 mg/L throughout the testing cycle of the low-range load (Figure 4.4) and the mid-range load (Figure 4.5).
- Overall, alkalinity concentrations increased with time as the wasteloads increased. For the low-range load, the nitrate (Figure 4.7), volatile acids (Figure 4.16), and phenol (Figure 4.19) concentrations did not change considerably throughout the testing cycle; whereas, their respective concentrations in the control increased steadily.
- The ORP of the low-range load was maintained above -100 mV which implied that the underdrain was not fully anaerobic. In general, AER and AERSE kept the ORP more positive than the control.
- The normalized COD and BOD of the AER system generally indicated a slightly
more stable system than the other systems in terms of COD and BOD control.

For the AER system of the low-range and high-range loads, the total solids concentration increased with time at a faster rate than the total solids concentration of the control, possibly implying that aerobic microbes were abundant.

The AERSE system followed the same trend of the AER system of the low-range and mid-range loads, except for the volatile acids, normalized BOD$_5$, and ORP of the mid-range load. The volatile acids concentration of the mid-range load remained higher than the concentrations found in the control. The normalized BOD$_5$ of this system tended to increase. Finally, the ORP of the mid-range load fell below -300 mV on Day 5 and remained at this level.

For the high-range load (Figure 4.6), AER and AERSE could not maintain aerobic conditions in the underdrain. The DO concentration dropped to 0.1 mg/L by Day 2, causing the underdrain to become anaerobic.

Neither AER nor AERSE reduced the production of ammonia and phosphate. Their concentrations increased with an increase in wasteload. AER and AERSE increased ammonia concentrations in the air phase compared to its control. This is expected because of the stripping effect caused by air spargings.

Results of odor analyses suggested that AER provided a distinct degree of odor abatement by reducing the overall odor intensity and many of its constituents. By inductive reasoning, it can be concluded that the AERSE system provided the best odor control, followed by the AER system as compared to the control system.
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APPENDIX A

PROPERTIES AND PHYSIOLOGICAL EFFECTS OF NOXIOUS GASES
Table A.1. Properties and physiological effects of noxious gases (Adapted from Taiganides and White, 1968).

<table>
<thead>
<tr>
<th>Gas</th>
<th>Biological Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Carbon Dioxide (CO₂) Asphyxiant</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Biological Impact:</strong></td>
<td></td>
</tr>
<tr>
<td>Density : 1.98 grams/liter</td>
<td></td>
</tr>
<tr>
<td>Specific gravity : 1.53</td>
<td></td>
</tr>
<tr>
<td>Odor : None</td>
<td></td>
</tr>
<tr>
<td>Color: None</td>
<td></td>
</tr>
<tr>
<td>Maximum allowable concentrations : 5,000 ppm</td>
<td></td>
</tr>
<tr>
<td>20,000 ppm concentration; Physiological effects : Safe</td>
<td></td>
</tr>
<tr>
<td>30,000 ppm concentration; Physiological effects : Increased breathing</td>
<td></td>
</tr>
<tr>
<td>40,000 ppm concentration; Physiological effects : Drowsiness, headaches</td>
<td></td>
</tr>
<tr>
<td>60,000 ppm concentration; Exposure period : 30 min.; Physiological effects : Heavy, asphyxiating breathing</td>
<td></td>
</tr>
<tr>
<td>300,000 ppm concentration; exposure period : 30 min.; Physiological effects : Could be fatal</td>
<td></td>
</tr>
<tr>
<td><strong>Ammonia (NH₃) Irritant</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Biological Impact:</strong></td>
<td></td>
</tr>
<tr>
<td>Density: 0.77 grams/liter</td>
<td></td>
</tr>
<tr>
<td>Specific gravity: 0.58</td>
<td></td>
</tr>
<tr>
<td>Odor: Sharp, pungent</td>
<td></td>
</tr>
<tr>
<td>Color: None</td>
<td></td>
</tr>
<tr>
<td>Explosive range: Minimum: 16; Maximum: Odor threshold: 5 ppm</td>
<td></td>
</tr>
<tr>
<td>Maximum allowable concentrations: 50 ppm</td>
<td></td>
</tr>
<tr>
<td>400 ppm concentration; Physiological effects: Throat irritant</td>
<td></td>
</tr>
<tr>
<td>700 ppm concentration; Physiological effects: Eye irritant</td>
<td></td>
</tr>
<tr>
<td>1,700 ppm concentration; Physiological effects: Coughing and frothing</td>
<td></td>
</tr>
<tr>
<td>3,000 ppm concentration; Exposure periods: 30 min.; Physiological effects: Asphyxiating</td>
<td></td>
</tr>
<tr>
<td>5, 000 ppm concentration; Exposure period: 40 min.; Physiological effects: Could be fatal</td>
<td></td>
</tr>
</tbody>
</table>
Table A.1 (Continued). Properties and physiological effects of noxious gases (Adapted from Taiganides and White, 1968).

<table>
<thead>
<tr>
<th>Gas</th>
<th>Biological Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hydrogen sulfide (H₂S) Poison</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Biological Impact:</strong></td>
<td></td>
</tr>
<tr>
<td>Density: 1.54 grams/liter</td>
<td></td>
</tr>
<tr>
<td>Specific gravity: 1.19</td>
<td></td>
</tr>
<tr>
<td>Odor: Rotten egg smell, nauseating</td>
<td></td>
</tr>
<tr>
<td>Color: None</td>
<td></td>
</tr>
<tr>
<td>Explosive range: Minimum: 4; Maximum: 46</td>
<td></td>
</tr>
<tr>
<td>Odor threshold: 0.7 ppm</td>
<td></td>
</tr>
<tr>
<td>Maximum allowable concentrations: 10 ppm</td>
<td></td>
</tr>
<tr>
<td>100 ppm concentration; Exposure period: several hours; Physiological effects: Irritation of the eyes and nose:</td>
<td></td>
</tr>
<tr>
<td>200 ppm concentration; Exposure period: 60 min.; Physiological effects: Headaches, dizziness</td>
<td></td>
</tr>
<tr>
<td>500 ppm concentration; Exposure period: 30 min.; Physiological effects: Nausea, excitement, insomnia</td>
<td></td>
</tr>
<tr>
<td>1,000 ppm concentration; Physiological effects: Unconsciousness, death</td>
<td></td>
</tr>
<tr>
<td><strong>Methane (CH₄) Asphyxiant</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Biological Impact:</strong></td>
<td></td>
</tr>
<tr>
<td>Density: 0.72 grams/liter</td>
<td></td>
</tr>
<tr>
<td>Specific gravity: 0.58</td>
<td></td>
</tr>
<tr>
<td>Odor: None</td>
<td></td>
</tr>
<tr>
<td>Color: None</td>
<td></td>
</tr>
<tr>
<td>Explosive range: Minimum: 5; Maximum: 15</td>
<td></td>
</tr>
<tr>
<td>Maximum allowable concentrations: 1,000 ppm</td>
<td></td>
</tr>
<tr>
<td>500,000 ppm concentration; Physiological effects: Headache, nontoxic</td>
<td></td>
</tr>
<tr>
<td><strong>Carbon monoxide (CO) Poison</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Biological Impact:</strong></td>
<td></td>
</tr>
<tr>
<td>Density: 1.25 grams/liter</td>
<td></td>
</tr>
<tr>
<td>Specific gravity: 0.97</td>
<td></td>
</tr>
<tr>
<td>Odor: None</td>
<td></td>
</tr>
<tr>
<td>Color: None</td>
<td></td>
</tr>
<tr>
<td>Maximum allowable concentrations: 50 ppm</td>
<td></td>
</tr>
<tr>
<td>500 ppm concentration; Exposure period: 60 min.; Physiological effects: None</td>
<td></td>
</tr>
<tr>
<td>1,000 ppm concentration; Exposure period: 60 min.; Physiological effects: Unpleasant, but not dangerous</td>
<td></td>
</tr>
<tr>
<td>2,000 ppm concentration; Exposure period: 60 min.; Physiological effects: Dangerous</td>
<td></td>
</tr>
<tr>
<td>4,000 ppm concentration; Exposure period: 60+ min.; Physiological effects: Fatal</td>
<td></td>
</tr>
</tbody>
</table>
Table A.1 (Continued). Properties and physiological effects of noxious gases (Adapted from Taiganides and White, 1968).

<table>
<thead>
<tr>
<th><strong>Air</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Biological Impact:</strong></td>
<td>Density: Density of the gases in grams per liter at 32 degrees F. Density of air is 1.29 grams/liter.</td>
</tr>
<tr>
<td></td>
<td>Specific gravity: the ratio of the weight of pure gas to that of atmospheric air. If the number is less than 1, the gas is lighter than air; if greater than 1, it is heavier than air.</td>
</tr>
<tr>
<td></td>
<td>Explosive range: The range within which a mixture of gas and atmospheric air can explode with a spark (percent by volume).</td>
</tr>
<tr>
<td></td>
<td>Odor threshold: The lowest concentration at which the odor is detected. This figure can only be approximate.</td>
</tr>
<tr>
<td></td>
<td>Maximum allowable concentration: The concentration set by health agencies as the maximum allowed in an atmosphere where men work over an 8- to 10-hour period. Possible the levels should be lower for animals since they must be in the environment continuously.</td>
</tr>
<tr>
<td></td>
<td>Concentrations: In parts of pure gas per million parts of atmospheric air. To change to percent by volume, divide by 10,000.</td>
</tr>
<tr>
<td></td>
<td>Exposure period: The time during which the effects of the noxious gas are felt by an adult human or a 150-pound pig.</td>
</tr>
<tr>
<td></td>
<td>Physiological effects: Those found to occur in adult humans. Similar effect would be felt by a 150-pound pig. Lighter pigs would be affected sooner at lower rates.</td>
</tr>
</tbody>
</table>
APPENDIX B

PIG WEIGHT DATA
Table B.1. Approximate pig weight data from 9/1/99 - 11/11/99

<table>
<thead>
<tr>
<th>Date</th>
<th>Day</th>
<th>Weight (lbs)</th>
<th># pigs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Left Pen</td>
<td>Right Pen</td>
</tr>
<tr>
<td>9/14/99</td>
<td>1</td>
<td>140</td>
<td>140</td>
</tr>
<tr>
<td>11/11/99</td>
<td>59</td>
<td>220</td>
<td>220</td>
</tr>
</tbody>
</table>

Growth Rate Equation:  

\[ y = 1.3793x + 138.62 \]

Table B.2. Approximate pig weight data from 2/3/00 - 5/10/00

<table>
<thead>
<tr>
<th>Date</th>
<th>Day</th>
<th>Weight (lbs)</th>
<th># pigs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Left Pen</td>
<td>Right Pen</td>
</tr>
<tr>
<td>2/3/00</td>
<td>1</td>
<td>25.4</td>
<td>27.5</td>
</tr>
<tr>
<td>4/7/00</td>
<td>65</td>
<td>94.3</td>
<td>111.2</td>
</tr>
<tr>
<td>5/10/00</td>
<td>98</td>
<td>162.3</td>
<td>181.4</td>
</tr>
<tr>
<td>5/10/00</td>
<td>98</td>
<td>166.3</td>
<td>189.8</td>
</tr>
</tbody>
</table>

Growth Rate Equation:  

Left -> \[ y = 1.3651x + 19.347 \]  
Right -> \[ y = 1.5488x + 22.028 \]
APPENDIX C

RAW DATA
Table C.1. Date and COD load for the control testing cycle

<table>
<thead>
<tr>
<th>Date</th>
<th>Load lb COD</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/22/99 - 9/29/99</td>
<td>78</td>
</tr>
<tr>
<td>9/29/99 - 10/6/99</td>
<td>83</td>
</tr>
<tr>
<td>11/03/99-11/10/99</td>
<td>107</td>
</tr>
<tr>
<td>2/10/00 - 2/17/00 (Left Pit)</td>
<td>17</td>
</tr>
<tr>
<td>2/10/00 - 2/17/00 (Right Pit)</td>
<td>20</td>
</tr>
<tr>
<td>3/15/00 - 3/22/00 (Left Pit)</td>
<td>42</td>
</tr>
<tr>
<td>3/15/00 - 3/22/00 (Right Pit)</td>
<td>47</td>
</tr>
<tr>
<td>5/4/00 - 5/11/00 (Left Pit)</td>
<td>76</td>
</tr>
<tr>
<td>5/4/00 - 5/11/00 (Right Pit)</td>
<td>86</td>
</tr>
<tr>
<td>4/24/00 - 5/31/00</td>
<td>51</td>
</tr>
<tr>
<td>5/31/00 - 6/6/00</td>
<td>54</td>
</tr>
<tr>
<td>6/14/00 - 6/21/00</td>
<td>60</td>
</tr>
</tbody>
</table>
Table C.2. Date and COD load for the aeration testing cycle

<table>
<thead>
<tr>
<th>Date</th>
<th>Load lb COD</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/6/99 - 10/13/00</td>
<td>88</td>
</tr>
<tr>
<td>10/13/99 - 10/20/99</td>
<td>93</td>
</tr>
<tr>
<td>10/20/00 - 10/27/00</td>
<td>98</td>
</tr>
<tr>
<td>2/24/00 - 3/1/00 (Left Pit)</td>
<td>22</td>
</tr>
<tr>
<td>2/24/00 - 3/1/00 (Right Pit)</td>
<td>25</td>
</tr>
<tr>
<td>3/22/00 - 3/29/00 (Left Pit)</td>
<td>46</td>
</tr>
<tr>
<td>3/22/00 - 3/29/00 (Right Pit)</td>
<td>53</td>
</tr>
<tr>
<td>5/11/00 - 5/18/00 (Left Pit)</td>
<td>40</td>
</tr>
<tr>
<td>5/11/00 - 5/18/00 (Right Pit)</td>
<td>46</td>
</tr>
<tr>
<td>5/24/00 - 5/31/00</td>
<td>45</td>
</tr>
</tbody>
</table>

Table C.3. Date and COD load for the aeration and seeding testing cycle

<table>
<thead>
<tr>
<th>Date</th>
<th>Load lb COD</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/27/99 - 11/03/99</td>
<td>103</td>
</tr>
<tr>
<td>3/1/00 - 3/8/00 (Left Pit)</td>
<td>32</td>
</tr>
<tr>
<td>3/1/00 - 3/8/00 (Right Pit)</td>
<td>36</td>
</tr>
<tr>
<td>4/12/00 - 4/19/00 (Left Pit)</td>
<td>61</td>
</tr>
<tr>
<td>4/12/00 - 4/19/00 (Right Pit)</td>
<td>70</td>
</tr>
<tr>
<td>5/31/00 - 6/6/00</td>
<td>48</td>
</tr>
</tbody>
</table>
Table C.4. Date and COD load for the low-range control testing cycle

<table>
<thead>
<tr>
<th>Date</th>
<th>Load lb COD</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/10/00 - 2/17/00 (Left Pit)</td>
<td>17</td>
</tr>
<tr>
<td>2/10/00 - 2/17/00 (Right Pit)</td>
<td>20</td>
</tr>
</tbody>
</table>

Table C.5. Date and COD load for the mid-range control testing cycle

<table>
<thead>
<tr>
<th>Date</th>
<th>Load lb COD</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/15/00 - 3/22/00 (Left Pit)</td>
<td>42</td>
</tr>
<tr>
<td>3/15/00 - 3/22/00 (Right Pit)</td>
<td>47</td>
</tr>
<tr>
<td>4/24/00 - 5/31/00</td>
<td>51</td>
</tr>
<tr>
<td>5/31/00 - 6/6/00</td>
<td>54</td>
</tr>
<tr>
<td>6/14/00 - 6/21/00</td>
<td>60</td>
</tr>
</tbody>
</table>

Table C.6. Date and COD load for the high-range control testing cycle

<table>
<thead>
<tr>
<th>Date</th>
<th>Load lb COD</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/22/99 - 9/29/99</td>
<td>78</td>
</tr>
<tr>
<td>9/29/99 - 10/6/99</td>
<td>83</td>
</tr>
<tr>
<td>11/03/99-11/10/99</td>
<td>107</td>
</tr>
<tr>
<td>5/4/00 - 5/11/00 (Left Pit)</td>
<td>76</td>
</tr>
<tr>
<td>5/4/00 - 5/11/00 (Right Pit)</td>
<td>86</td>
</tr>
</tbody>
</table>
Table C.7. Date and COD load for the low-range aeration testing cycle

<table>
<thead>
<tr>
<th>Date</th>
<th>Load lb COD</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/24/00 - 3/1/00 (Left Pit)</td>
<td>22</td>
</tr>
<tr>
<td>2/24/00 - 3/1/00 (Right Pit)</td>
<td>25</td>
</tr>
</tbody>
</table>

Table C.8. Date and COD load for the mid-range aeration testing cycle

<table>
<thead>
<tr>
<th>Date</th>
<th>Load lb COD</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/22/00 - 3/29/00 (Left Pit)</td>
<td>46</td>
</tr>
<tr>
<td>3/22/00 - 3/29/00 (Right Pit)</td>
<td>53</td>
</tr>
<tr>
<td>5/11/00 - 5/18/00 (Left Pit)</td>
<td>40</td>
</tr>
<tr>
<td>5/11/00 - 5/18/00 (Right Pit)</td>
<td>46</td>
</tr>
<tr>
<td>5/24/00 - 5/31/00</td>
<td>45</td>
</tr>
</tbody>
</table>

Table C.9. Date and COD load for the high-range aeration testing cycle

<table>
<thead>
<tr>
<th>Date</th>
<th>Load lb COD</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/6/99 - 10/13/00</td>
<td>88</td>
</tr>
<tr>
<td>10/13/99 - 10/20/99</td>
<td>93</td>
</tr>
<tr>
<td>10/20/00 - 10/27/00</td>
<td>98</td>
</tr>
</tbody>
</table>
Table C.10. Date and COD load for the low-range aeration and seeding testing cycle

<table>
<thead>
<tr>
<th>Date</th>
<th>Load lb COD</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/1/00 - 3/8/00 (Left Pit)</td>
<td>32</td>
</tr>
<tr>
<td>3/1/00 - 3/8/00 (Right Pit)</td>
<td>36</td>
</tr>
</tbody>
</table>

Table C.11. Date and COD load for the mid-range aeration and seeding testing cycle

<table>
<thead>
<tr>
<th>Date</th>
<th>Load lb COD</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/12/00 - 4/19/00 (Left Pit)</td>
<td>61</td>
</tr>
<tr>
<td>4/12/00 - 4/19/00 (Right Pit)</td>
<td>70</td>
</tr>
<tr>
<td>5/31/00 - 6/6/00</td>
<td>48</td>
</tr>
</tbody>
</table>

Table C.12. Date and COD load for the high-range aeration and seeding testing cycle

<table>
<thead>
<tr>
<th>Date</th>
<th>Load lb COD</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/27/99 - 11/03/99</td>
<td>103</td>
</tr>
</tbody>
</table>
APPENDIX D

RAW WATER QUALITY DATA
### Table D.1. Raw water quality data for the control 9/22/99 - 9/29/99

<table>
<thead>
<tr>
<th>Time</th>
<th>Sample Location</th>
<th>DO</th>
<th>BOD</th>
<th>COD</th>
<th>TS</th>
<th>PO$_4^-$</th>
<th>ORP</th>
<th>pH</th>
<th>NH$_3$</th>
<th>Alk</th>
<th>Phenol</th>
<th>NO$_3^-$</th>
<th>VAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 d</td>
<td>RS</td>
<td>--</td>
<td>383</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>550</td>
<td>1.53</td>
<td>936</td>
<td>107</td>
<td></td>
</tr>
<tr>
<td>2 d</td>
<td>RD</td>
<td>--</td>
<td>410</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>530</td>
<td>2.06</td>
<td>372</td>
<td>197</td>
<td></td>
</tr>
<tr>
<td>7 d</td>
<td>RS</td>
<td>--</td>
<td>911</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1500</td>
<td>1.52</td>
<td>730</td>
<td>98</td>
<td></td>
</tr>
<tr>
<td>7 d</td>
<td>RD</td>
<td>--</td>
<td>887</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1350</td>
<td>1.26</td>
<td>387</td>
<td>151</td>
<td></td>
</tr>
</tbody>
</table>

R-Right pit
S-sample from the shallow end of pit
D-sample from the deep end of pit
Alk-Alkalinity

Approximate Load - 78 lbs COD/test period

### Table D.2. Raw water quality data for the control 9/29/99 - 10/06/99

<table>
<thead>
<tr>
<th>Time</th>
<th>Sample Location</th>
<th>DO</th>
<th>BOD</th>
<th>COD</th>
<th>TS</th>
<th>PO$_4^-$</th>
<th>ORP</th>
<th>pH</th>
<th>NH$_3$</th>
<th>Alk</th>
<th>Phenol</th>
<th>NO$_3^-$</th>
<th>VAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 d</td>
<td>RS</td>
<td>--</td>
<td>444</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>275</td>
<td>0.22</td>
<td>26</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2 d</td>
<td>RD</td>
<td>--</td>
<td>336</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>575</td>
<td>0.81</td>
<td>452</td>
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</tr>
<tr>
<td>7 d</td>
<td>RS</td>
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<td>755</td>
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<tr>
<td>7 d</td>
<td>RD</td>
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<td>--</td>
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<td>1236</td>
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</tr>
</tbody>
</table>

R-Right pit
S-sample from the shallow end of pit
D-sample from the deep end of pit
Alk-Alkalinity

Approximate Load - 83 lbs COD/test period
### Table D.3. Raw water quality data for the control 11/03/99 - 11/10/99

<table>
<thead>
<tr>
<th>Time d</th>
<th>Sample Location</th>
<th>DO mg/L</th>
<th>BOD mg/L</th>
<th>COD mg/L</th>
<th>TS mg/L</th>
<th>PO₄³⁻ mg/L</th>
<th>ORP mV</th>
<th>pH</th>
<th>NH₃ mg/L</th>
<th>Alk mg/L</th>
<th>Phenol mg/L</th>
<th>NO₃⁻ mg/L</th>
<th>VAs mg/L</th>
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<tbody>
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</tr>
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<td>RS</td>
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<td>--</td>
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<td>--</td>
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</table>

R-Right pit  
S-sample from the shallow end of pit  
D-sample from the deep end of pit  
Alk-Alkalinity  

Approximate Load - 107 lbs COD/test period
Table D.4. Raw water quality data for the control 2/10/00 - 2/17/00

<table>
<thead>
<tr>
<th>Time</th>
<th>Sample Location</th>
<th>DO (mg/L)</th>
<th>BOD (mg/L)</th>
<th>COD (mg/L)</th>
<th>TS (mg/L)</th>
<th>PO$_4^{3-}$ (mg/L)</th>
<th>ORP (mV)</th>
<th>pH</th>
<th>NH$_3$ (mg/L)</th>
<th>Alk (mg/L)</th>
<th>Phenol (mg/L)</th>
<th>NO$_3^-$ (mg/L)</th>
<th>VAs (mg/L)</th>
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</thead>
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<td>1</td>
<td>260</td>
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<tr>
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<td>--</td>
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<td>230</td>
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R-Right pit
S-sample from the shallow end of pit
D-sample from the deep end of pit
Alk-Alkalinity

Approximate Load - 17 lbs COD/test period
Table D.5. Raw water quality data for the control 2/10/00 - 2/17/00

<table>
<thead>
<tr>
<th>Time</th>
<th>Sample Location</th>
<th>DO mg/L</th>
<th>BOD mg/L</th>
<th>COD mg/L</th>
<th>TS mg/L</th>
<th>PO$_4^{3-}$ mg/L</th>
<th>ORP mV</th>
<th>pH</th>
<th>NH$_3$ mg/L</th>
<th>Alk mg/L</th>
<th>Phenol mg/L</th>
<th>NO$_3^-$ mg/L</th>
<th>VAs mg/L</th>
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<td>0</td>
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<td>1</td>
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</table>

L-Left pit  
S-sample from the shallow end of pit  
D-sample from the deep end of pit  
Alk-Alkalinity  
Approximate Load - 20 lbs COD/test period
Table D.6. Raw water quality data for the control 3/15/00 - 3/22/00

<table>
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<th>Time</th>
<th>Sample Location</th>
<th>DO (mg/L)</th>
<th>BOD (mg/L)</th>
<th>COD (mg/L)</th>
<th>TS (mg/L)</th>
<th>PO₄³⁻ (mg/L)</th>
<th>ORP (mV)</th>
<th>pH</th>
<th>NH₃ (mg/L)</th>
<th>Alk (mg/L)</th>
<th>Phenol (mg/L)</th>
<th>NO₃⁻ (mg/L)</th>
<th>VAs (mg/L)</th>
</tr>
</thead>
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<td>220</td>
<td>0.01</td>
<td>62</td>
<td>6</td>
</tr>
<tr>
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<td>--</td>
<td>--</td>
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<tr>
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<td>3900</td>
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R-Right pit
S-sample from the shallow end of pit
D-sample from the deep end of pit
ND-None-detectable
Alk-Alkalinity

Approximate Load - 42 lbs COD/test period
Table D.7. Raw water quality data for the control 3/15/00 - 3/22/00

<table>
<thead>
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<th>Time d</th>
<th>Sample Location</th>
<th>DO mg/L</th>
<th>BOD mg/L</th>
<th>COD mg/L</th>
<th>TS mg/L</th>
<th>PO_{4}^{3} mg/L</th>
<th>ORP mV</th>
<th>pH</th>
<th>NH_{3} mg/L</th>
<th>Alk mg/L</th>
<th>Phenol mg/L</th>
<th>NO_{3} mg/L</th>
<th>VAs mg/L</th>
</tr>
</thead>
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<tr>
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<td>RS</td>
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<td>302</td>
<td>3</td>
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<td>28</td>
<td>220</td>
<td>0.01</td>
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<td>6</td>
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<tr>
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L-Left pit
S-sample from the shallow end of pit
D-sample from the deep end of pit
Alk-Alkalinity

Approximate Load - 47 lbs COD/test period
Table D.8. Raw water quality data for the control 5/4/00 - 5/11/00

<table>
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<tr>
<th>Time (d)</th>
<th>Sample Location</th>
<th>DO (mg/L)</th>
<th>BOD (mg/L)</th>
<th>COD (mg/L)</th>
<th>TS (mg/L)</th>
<th>PO$_4^{3-}$ (mg/L)</th>
<th>ORP (mV)</th>
<th>pH</th>
<th>NH$_3$ (mg/L)</th>
<th>Alk (mg/L)</th>
<th>Phenol (mg/L)</th>
<th>NO$_3^-$ (mg/L)</th>
<th>VAs (mg/L)</th>
</tr>
</thead>
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R-Right pit
S-sample from the shallow end of pit
D-sample from the deep end of pit
Alk-Alkalinity

Approximate Load - 76 lbs COD/test period
Table D.9. Raw water quality data for the control 5/4/00 - 5/11/00

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<th>TS</th>
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<th>ORP</th>
<th>pH</th>
<th>NH$_3$</th>
<th>Alk</th>
<th>Phenol</th>
<th>NO$_3^-$</th>
<th>VAs</th>
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<td>mg/L</td>
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L-Left pit  
S-sample from the shallow end of pit  
D-sample from the deep end of pit  
Alk-Alkalinity  

Approximate Load - 86 lbs COD/test period
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<th>COD mg/L</th>
<th>TS mg/L</th>
<th>PO₄³⁻ mg/L</th>
<th>ORP mV</th>
<th>pH</th>
<th>NH₃ mg/L</th>
<th>Alk mg/L</th>
<th>Phenol mg/L</th>
<th>NO₃ mg/L</th>
<th>VAs mg/L</th>
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R-Right pit
S-sample from the shallow end of pit
D-sample from the deep end of pit
Alk-Alkalinity

Approximate Load - 51 lbs COD/test period
Table D.11. Raw water quality data for the control 5/31/00 - 6/6/00

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<th>COD mg/L</th>
<th>TS mg/L</th>
<th>PO₄³⁻ mg/L</th>
<th>ORP mV</th>
<th>pH</th>
<th>NH₃ mg/L</th>
<th>Alk mg/L</th>
<th>Phenol mg/L</th>
<th>NO₃ mg/L</th>
<th>VAs mg/L</th>
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R-Right pit
S-sample from the shallow end of pit
D-sample from the deep end of pit
Alk-Alkalinity

Approximate Load - 54 lbs COD/test period
Table D.12. Raw water quality data for the control 6/14/00 - 6/21/00

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<th>ORP</th>
<th>pH</th>
<th>NH$_3$</th>
<th>Alk</th>
<th>Phenol</th>
<th>NO$_3$</th>
<th>VAs</th>
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R-Right pit  
S-sample from the shallow end of pit  
D-sample from the deep end of pit  
Alk-Alkalinity  
Approximate Load - 60 lbs COD/test period
### Table D.13. Raw water quality data for the aeration with 15 minutes cycled on and off 10/06/99 - 10/13/99

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<th>BOD mg/L</th>
<th>COD mg/L</th>
<th>TS mg/L</th>
<th>PO$_4^{3-}$ mg/L</th>
<th>ORP mV</th>
<th>pH</th>
<th>NH$_3$ mg/L</th>
<th>Alk mg/L</th>
<th>Phenol mg/L</th>
<th>NO$_3$ mg/L</th>
<th>VAs mg/L</th>
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R-Right pit  
S-sample from the shallow end of pit  
D-sample from the deep end of pit  
Alk-Alkalinity

Approximate Load - 88 lbs COD/test period

### Table D14. Raw water quality data for the aeration 10/13/99 - 10/20/99

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<th>COD mg/L</th>
<th>TS mg/L</th>
<th>PO$_4^{3-}$ mg/L</th>
<th>ORP mV</th>
<th>pH</th>
<th>NH$_3$ mg/L</th>
<th>Alk mg/L</th>
<th>Phenol mg/L</th>
<th>NO$_3$ mg/L</th>
<th>VAs mg/L</th>
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</thead>
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<td>571</td>
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R-Right pit  
S-sample from the shallow end of pit  
D-sample from the deep end of pit  
Alk-Alkalinity

Approximate Load - 93 lbs COD/test period
Table D.15. Raw water quality data for the aeration 10/20/99 - 10/27/99

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<th>Sample Location</th>
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<th>BOD mg/L</th>
<th>COD mg/L</th>
<th>TS mg/L</th>
<th>PO₄³⁻ mg/L</th>
<th>ORP mV</th>
<th>pH</th>
<th>NH₃ mg/L</th>
<th>Alk mg/L</th>
<th>Phenol mg/L</th>
<th>NO₃⁻ mg/L</th>
<th>VAs mg/L</th>
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R-Right pit  
S-sample from the shallow end of pit  
D-sample from the deep end of pit  
Alk-Alkalinity  

Approximate Load - 98 lbs COD/test period
Table D.16. Raw water quality data for the aeration 2/24/00 - 3/1/00

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<th>Time</th>
<th>Sample Location</th>
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<th>BOD mg/L</th>
<th>COD mg/L</th>
<th>TS mg/L</th>
<th>PO$_4^{3-}$ mg/L</th>
<th>ORP mV</th>
<th>pH</th>
<th>NH$_3$ mg/L</th>
<th>Alk mg/L</th>
<th>Phenol mg/L</th>
<th>NO$_3^-$ mg/L</th>
<th>VAs mg/L</th>
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R-Right pit
S-sample from the shallow end of pit
D-sample from the deep end of pit
Alk-Alkalinity

Approximate Load - 22 lbs COD/test period
Table D.17. Raw water quality data for the aeration 2/24/00 - 3/1/00

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<th>COD mg/L</th>
<th>TS mg/L</th>
<th>PO₄³⁻ mg/L</th>
<th>ORP mV</th>
<th>pH</th>
<th>NH₃ mg/L</th>
<th>Alk mg/L</th>
<th>Phenol mg/L</th>
<th>NO₃⁻ mg/L</th>
<th>VAs mg/L</th>
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<td>0.17</td>
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L-Left pit  
S-sample from the shallow end of pit  
D-sample from the deep end of pit  
Alk-Alkalinity  
Approximate Load - 25 lbs COD/test period
### Table D.18. Raw water quality data for the aeration 3/22/00 - 3/29/00

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<th>BOD mg/L</th>
<th>COD mg/L</th>
<th>TS mg/L</th>
<th>PO$_4^-$ mg/L</th>
<th>ORP mV</th>
<th>pH</th>
<th>NH$_3$ mg/L</th>
<th>Alk mg/L</th>
<th>Phenol mg/L</th>
<th>NO$_3$ mg/L</th>
<th>VAs mg/L</th>
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R-Right pit
S-sample from the shallow end of pit
D-sample from the deep end of pit
Alk-Alkalinity

Approximate Load - 46 lbs COD/test period
Table D.19. Raw water quality data for the aeration 3/22/00 - 3/29/00

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<th>BOD mg/L</th>
<th>COD mg/L</th>
<th>TS mg/L</th>
<th>PO$_4^-$ mg/L</th>
<th>ORP mV</th>
<th>pH</th>
<th>NH$_3$ mg/L</th>
<th>Alk mg/L</th>
<th>Phenol mg/L</th>
<th>NO$_3$ mg/L</th>
<th>VAs mg/L</th>
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L-Left pit
S-sample from the shallow end of pit
D-sample from the deep end of pit
Alk-Alkalinity

Approximate Load - 53 lbs COD/test period
Table D.20. Raw water quality data for the aeration 5/11/00 - 5/18/00

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<th>TS</th>
<th>PO₄³⁻</th>
<th>ORP</th>
<th>pH</th>
<th>NH₃</th>
<th>Alk</th>
<th>Phenol</th>
<th>NO₃⁻</th>
<th>VAs</th>
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<td>mg/L</td>
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R-Right pit
S-sample from the shallow end of pit
D-sample from the deep end of pit
Alk-Alkalinity

Approximate Load - 40 lbs COD/test period
### Table D.21. Raw water quality data for the aeration 5/11/00 - 5/18/00

<table>
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<tr>
<th>Time (d)</th>
<th>Sample Location</th>
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<th>BOD (mg/L)</th>
<th>COD (mg/L)</th>
<th>TS (mg/L)</th>
<th>PO₄³⁻ (mg/L)</th>
<th>ORP (mV)</th>
<th>pH</th>
<th>NH₃ (mg/L)</th>
<th>Alk (mg/L)</th>
<th>Phenol (mg/L)</th>
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L-Left pit  
S-sample from the shallow end of pit  
D-sample from the deep end of pit  
Alk-Alkalinity  
Approximate Load - 46 lbs COD/test period
Table D.22. Raw water quality data for the aeration 5/24/00 - 5/31/00

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<th>NO$_3$</th>
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L-Left pit
S-sample from the shallow end of pit
D-sample from the deep end of pit
Alk-Alkalinity

Approximate Load - 45 lbs COD/test period
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<th>NH₃</th>
<th>Alk</th>
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R-Right pit
S-sample from the shallow end of pit
D-sample from the deep end of pit
Alk-Alkalinity

Approximate Load - 103 lbs COD/test period
Table D.24. Raw water quality data for the aeration and seeding 3/1/00 - 3/8/00

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<th>ORP (mV)</th>
<th>pH</th>
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R-Right pit
S-sample from the shallow end of pit
D-sample from the deep end of pit
Alk-Alkalinity

Approximate Load - 32 lbs COD/test period
Table D.25. Raw water quality data for the aeration and seeding 3/1/00 - 3/8/00

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L-Left pit  
S-sample from the shallow end of pit  
D-sample from the deep end of pit  
ND-None-detectable  
Alk-Alkalinity  

Approximate Load - 36 lbs COD/test period
Table D.26. Raw water quality data for the aeration and seeding 4/12/00 - 4/19/00

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<td>--</td>
<td>180</td>
<td>1077</td>
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R-Right pit  
S-sample from the shallow end of pit  
D-sample from the deep end of pit  
Alk-Alkalinity  

Approximate Load - 61 lbs COD/test period
### Table D.27. Raw water quality data for the aeration and seeding 4/12/00 - 4/19/00

<table>
<thead>
<tr>
<th>Time d</th>
<th>Sample Location</th>
<th>DO mg/L</th>
<th>BOD mg/L</th>
<th>COD mg/L</th>
<th>TS mg/L</th>
<th>PO₄³⁻ mg/L</th>
<th>ORP mV</th>
<th>pH</th>
<th>NH₃ mg/L</th>
<th>Alk mg/L</th>
<th>Phenol mg/L</th>
<th>NO₃⁻ mg/L</th>
<th>VAs mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LS</td>
<td>0.2</td>
<td>156</td>
<td>682</td>
<td>1204</td>
<td>8</td>
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<td>270</td>
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</tr>
<tr>
<td>1</td>
<td>LD</td>
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<td>365</td>
<td>0</td>
<td>280</td>
<td>6</td>
<td>-280</td>
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<td>45</td>
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<td>370</td>
<td>31</td>
</tr>
<tr>
<td>2</td>
<td>LS</td>
<td>0.1</td>
<td>--</td>
<td>1158</td>
<td>1384</td>
<td>12</td>
<td>-269</td>
<td>7.8</td>
<td>165</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
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<td>LD</td>
<td>0.3</td>
<td>--</td>
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<td>1364</td>
<td>19</td>
<td>-145</td>
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<td>35</td>
<td>--</td>
<td>7.7</td>
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<td>2285</td>
<td>--</td>
<td>85</td>
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<td>LD</td>
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<td>2793</td>
<td>3384</td>
<td>33</td>
<td>--</td>
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<td>665</td>
<td>2255</td>
<td>--</td>
<td>160</td>
<td>1499</td>
</tr>
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</table>

- L-Left pit
- S-sample from the shallow end of pit
- D-sample from the deep end of pit
- Alk-Alkalinity
- Approximate Load - 70 lbs COD/test period
Table D.28. Raw water quality data for the aeration and seeding 5/31/00 - 6/6/00

<table>
<thead>
<tr>
<th>Time</th>
<th>Sample Location</th>
<th>DO mg/L</th>
<th>BOD mg/L</th>
<th>COD mg/L</th>
<th>TS mg/L</th>
<th>PO₄³⁻ mg/L</th>
<th>ORP mV</th>
<th>pH</th>
<th>NH₃ mg/L</th>
<th>Alk mg/L</th>
<th>Phenol mg/L</th>
<th>NO₃⁻ mg/L</th>
<th>VAs mg/L</th>
</tr>
</thead>
<tbody>
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<td>LS</td>
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<td>690</td>
<td>582</td>
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<td>500</td>
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<td>LD</td>
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<td>712</td>
<td>502</td>
<td>9</td>
<td>-329</td>
<td>7.9</td>
<td>24</td>
<td>265</td>
<td>0.47</td>
<td>450</td>
<td>21.00</td>
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<td>LS</td>
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<td>--</td>
<td>431</td>
<td>431</td>
<td>10</td>
<td>-262</td>
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<td>43</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
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<td>LD</td>
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<td>--</td>
<td>360</td>
<td>360</td>
<td>11</td>
<td>-141</td>
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<td>LS</td>
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<td>--</td>
</tr>
</tbody>
</table>

L-Left pit  
S-sample from the shallow end of pit  
D-sample from the deep end of pit  
Alk-Alkalinity  
Approximate Load - 48 lbs COD/test period
APPENDIX E

AVERAGED WATER QUALITY DATA
Table E.1. Average water quality results for control, aeration, and aeration and seeding treatments for the low-range load

<table>
<thead>
<tr>
<th></th>
<th>Control Treatment</th>
<th>Aeration Treatment</th>
<th>Aeration and A.S. Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Day 1</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td><strong>DO mg/L</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0.2</td>
<td>0.4</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>BOD mg/L</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>--</td>
<td>0</td>
<td>63</td>
</tr>
<tr>
<td><strong>COD mg/L</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>230</td>
<td>609</td>
<td>1281</td>
</tr>
<tr>
<td><strong>TS mg/L</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>188</td>
<td>408</td>
<td>991</td>
<td>1335</td>
</tr>
<tr>
<td><strong>PO₄³⁻ mg/L</strong></td>
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<td></td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>16</td>
<td>23</td>
</tr>
<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>125</td>
<td>49</td>
<td>-178</td>
<td>-192</td>
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<tr>
<td><strong>pH</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.5</td>
<td>7.4</td>
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</tr>
<tr>
<td><strong>NH₃ mg/L</strong></td>
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<td></td>
</tr>
<tr>
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<td>21</td>
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<td>81</td>
</tr>
<tr>
<td><strong>Alk mg/L</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>119</td>
<td>--</td>
<td>204</td>
<td>505</td>
</tr>
<tr>
<td><strong>Phenol mg/L</strong></td>
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<td></td>
</tr>
<tr>
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<td>0.83</td>
<td>0.91</td>
</tr>
<tr>
<td><strong>NO₃⁻ mg/L</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>96</td>
<td>--</td>
<td>171</td>
<td>54</td>
</tr>
<tr>
<td><strong>VAs mg/L</strong></td>
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<td></td>
</tr>
<tr>
<td>0</td>
<td>--</td>
<td>136</td>
<td>285</td>
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</tbody>
</table>

ND-No data
Table E.2. Average water quality results for control, aeration, and aeration and seeding treatments for the mid-range load

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<th>Aeration Treatment</th>
<th>Aeration and A.S. Treatment</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Day 1</td>
<td>Day 2</td>
<td>Day 5</td>
</tr>
<tr>
<td><strong>DO mg/L</strong></td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>BOD mg/L</strong></td>
<td>61</td>
<td>--</td>
<td>888</td>
</tr>
<tr>
<td><strong>COD mg/L</strong></td>
<td>244</td>
<td>509</td>
<td>1728</td>
</tr>
<tr>
<td><strong>TS mg/L</strong></td>
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<td>651</td>
<td>1504</td>
</tr>
<tr>
<td><strong>PO₄³⁻ mg/L</strong></td>
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<td>12</td>
<td>36</td>
</tr>
<tr>
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<td>-324</td>
</tr>
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<td>6.8</td>
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<td>1.11</td>
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ND-No data
Table E.3. Average water quality results for control, aeration, and aeration and seeding treatments for the high-range load

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<th>Aeration and A.S. Treatment</th>
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</thead>
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<td>Day</td>
<td>Day</td>
<td>Day</td>
</tr>
<tr>
<td>Day</td>
<td>1</td>
<td>2</td>
<td>5</td>
</tr>
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<td>DO mg/L</td>
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<td>0.1</td>
<td>0.2</td>
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