2002

An investigation into electrostatic water treatment systems

C. Alexis Bennett

Lehigh University

Follow this and additional works at: http://preserve.lehigh.edu/etd

Recommended Citation


This Thesis is brought to you for free and open access by Lehigh Preserve. It has been accepted for inclusion in Theses and Dissertations by an authorized administrator of Lehigh Preserve. For more information, please contact preserve@lehigh.edu.
Bennett, C. Alexis

An Investigation Into Electrostatic Water Treatment Systems

January 2003
An Investigation Into Electrostatic Water Treatment

Systems

by

C. Alexis Bennett

A Thesis
Presented to the Graduate and Research Committee
of Lehigh University
in Candidacy for the Degree of
Masters of Science
in
Mechanical Engineering and Mechanics

Lehigh University
September 6, 2002
This thesis is accepted and approved in the partial fulfillment of the requirements for the Masters of Science.

9/6/02
Date

John P. Quilten, Thesis Advisor

Herman F. Nied, Chairperson
Department of Mechanical Engineering and Mechanics
ACKNOWLEDGMENTS

First I would like to thank my parents Glyn and Susan Rowlands for their unconditional love and support throughout my life. They have always offered me the perfect hand of guidance by giving me supportive direction in times of need but also allowing me to discover life by myself, creating the individual that I am today.

I would also like to thank my loving grandparents Roger and Carolyn Turner for making my whole college career possible. They have shown me the meaning and power of truth and honesty. I hope that I will always make them proud.

Next I would like to thank my advisor Dr. Coulter. He always supported this project above and beyond capabilities of a normal human being. From him I have learned the significance of possessing excellent leadership skills. Without his qualities this project would not have carried on.

I would also like to give a special thanks to Paul McLaine for his funding, creativity and charisma. In addition I would like to thank the Ben Franklin Technology Partners for approving and funding this project.

A special thanks also goes out to Dr. Silebi, Dr. Llyod and Paul Burgmayer for teaching me chemistry and Dr. Knight for taking the time to teach me about bacteria testing procedures.

Finally I would like to thank all of my friends for always being there for me when I need you the most.

Thank you all very much
# TABLE OF CONTENTS

ACKNOWLEDGMENTS.................................................................................................................. iii

TABLE OF CONTENTS.................................................................................................................. iv

LIST OF TABLES .............................................................................................................................. ix

LIST OF FIGURES .......................................................................................................................... xi

ABSTRACT ......................................................................................................................................... 1

CHAPTER 1: Introduction to Electrostatic Water Treatment......................................................... 3

1.1 Water Treatment and Fouling Background.............................................................................. 3

1.1.1 Chemical Solutions to Fouling Background........................................................................ 4

1.1.2 Electrostatic Water Treatment ............................................................................................. 4

1.2 Objective of the Present Investigation .................................................................................... 5

1.3 Thesis Structure ....................................................................................................................... 5

CHAPTER 2: A Review of Fouling.................................................................................................... 9

2.1 Types of Fouling ....................................................................................................................... 9

2.1.1 Crystallization or Precipitation Fouling .............................................................................. 9

2.1.2 Particulate or Sludge Fouling ............................................................................................. 11

2.1.3 Chemical Reaction Fouling ................................................................................................ 11

2.1.4 Corrosion Fouling .............................................................................................................. 11

2.1.5 Biological Fouling .............................................................................................................. 12

2.1.6 Freezing Fouling ................................................................................................................ 13

2.2 The Complete Process of Fouling .......................................................................................... 13

2.2.1 Initiation Process ................................................................................................................. 13

2.2.2 Transport Process .............................................................................................................. 14

2.2.3 Attachment Process .......................................................................................................... 17

2.2.3.1 Van Der Waals Forces .................................................................................................. 17

2.2.3.2 Double Layer Force and Zeta Potential ....................................................................... 18

2.2.3.3 Balance Between Van der Waals and Electrostatic Repulsion Forces .................. 19

2.2.4 Removal Process .............................................................................................................. 21

2.2.5 Aging Process ................................................................................................................... 21

2.3 Efficiency Effects of Fouling .................................................................................................. 21

2.3.1 Thermal Efficiency in Fouling Conditions ....................................................................... 22

2.3.2 Pressure Drop Due to Fouling ........................................................................................ 25
2.4 Models Used to Simulate The Fouling Process ................................. 26
  2.4.1 Kern-Seaton Model ................................................................. 27
  2.4.2 Watkinson-Epstein Model ....................................................... 29

2.5 The Mechanics of Calcium Carbonate Scale Formation ..................... 30
  2.5.1 Calcium Carbonate Equilibrium .............................................. 31
  2.5.2 Solubility of Calcium Carbonate ............................................ 31
    2.5.2.1 Effects of Temperature on the Solubility of CaCO₃ ............... 32
    2.5.2.2 Effects of pH on the Solubility of CaCO₃ ......................... 33
    2.5.2.3 Effects of Pressure on the Solubility of CaCO₃ ................. 34
  2.5.3 Calcium Carbonate Precipitation Index .................................. 35
    2.5.3.1 Langlier Saturation Index ............................................ 37
    2.5.3.2 Ryznar Stability Index ............................................... 38
  2.5.4 Types of Calcium Carbonate Scale ....................................... 39
    2.5.4.1 Physical Characteristics of Calcite .............................. 39
    2.5.4.2 Physical Characteristics of Aragonite ........................... 40
    2.5.4.3 Physical Characteristics of Vaterite ............................ 40

CHAPTER 3: Treatments for Calcium Carbonate Scale Reduction ............... 42
  3.1 Natural Inhibitors to Calcium Carbonate Scale Formation ............... 43
    3.1.1 Calcite Growth Inhibition by Copper(II) ............................ 43
    3.1.2 Calcite Growth Inhibition by Iron(II) ............................... 44
  3.2 Traditional Chemical Treatment .......................................... 45
  3.3 Non-Traditional Chemical and Non-Chemical Water Treatment .......... 46
    3.3.1 Ion Exchange Water Treatment ........................................ 46
    3.3.2 Ozonation Water Treatment ............................................. 47
    3.3.3 Reverse Osmosis Water Treatment .................................... 47
    3.3.4 Vortex Technology Water Treatment .................................. 48
  3.4 Non-Chemical Magnetic and Electromagnetic Water Treatment .......... 48
    3.4.1 Magnetic Water Treatment .............................................. 49
    3.4.2 Electromagnetic Water Treatment ..................................... 50
      3.4.2.1 Studies Conducted at Drexel University ...................... 51
      3.4.2.2 Studies Completed at the University of Connecticut .......... 52
    3.4.3 Effects of Radiofrequency on Calcium Carbonate .................. 52
  3.5 Electrostatic Water Treatment ............................................ 53
    3.5.1 Manufacturers of Electrostatic Water Treatment Systems .......... 57
    3.5.2 Research Completed on Electrostatic Water Treatment and the Effect of Electrostatics on CaCO₃ Particles ................................. 58
      3.5.2.1 Experiment Completed by ProChemTech ....................... 59
3.5.2.2 Experiment Completed by Queensland University of Technology on Permaclean Water Treatment System .......................................................... 59
3.5.2.3 Tests on Non-chemical Scale Control Devices .............................................. 60
3.5.2.4 An Analytical Review of Water Conditioning Devices ..................................... 60
3.5.2.5 Studies on the Effects of CaCO₃ Particles in an Electric Field ....................... 61

CHAPTER 4: Investigation of the Electric Fields Associated With Electrostatic Water Treatment Technology .......................................................... 62

4.1 General Electrostatic Field Equations ............................................................. 62
4.2 Applied Electrostatic Field Equations ............................................................. 67
  4.2.1 Electric Field for Parallel Plate Resistors and Capacitors .............................. 67
  4.2.2 Electric Field for Cylindrical Geometries .................................................... 69
4.3 Electric Field in a Series Lossy Media ............................................................ 71
  4.3.1 Electric Field at Time t = 0 in Parallel Plate Series Lossy Media ................. 73
  4.3.2 Electric Field at Time t = ∞ in Parallel Plate Series Lossy Media .............. 74
  4.3.3 Electric Field at Time t = 0 in a Cylindrical Series Lossy Media ............... 76
  4.3.4 Electric Field at Time t = ∞ in a Cylindrical Series Lossy Media ............... 81
4.4 Comparison of Electric Fields In Cooling Water for Parallel Plate Lossy Media and Cylindrical Geometry Lossy Media at Time Infinity ............... 84

CHAPTER 5: Experimental Studies on the Effects of Electrostatic Water Treatment on Scale Growth and Removal .................................................. 87

5.1 Description of Test Apparatus ........................................................................ 87
  5.1.1 Components of Test Apparatus ................................................................. 88
  5.1.2 Description of Deposit Plates ..................................................................... 90
5.2 Test Method ................................................................................................... 91
  5.2.1 The Addition of Chemicals to Achieve Required Sump Chemistry .............. 92
    5.2.1.1 Chemicals Added to Achieve Crystallization Fouling ............................ 93
    5.2.1.2 Chemicals Added with the addition of Sodium Carbonate to Achieve Crystallization Fouling ................................................................. 94
    5.2.1.3 Chemicals Added to Achieve Particulate Fouling ................................. 96
  5.2.2 Temperature Measurements ................................................................... 98
  5.2.3 Flow Measurements .................................................................................. 99
  5.2.4 Cleaning of the System ............................................................................ 99
  5.2.5 Measurement of Scale Deposition .............................................................. 100
5.3 Results .......................................................................................................... 100
  5.3.1 The Studies of The Effects of Electrostatic Water Treatment on Crystallization Fouling .......................................................................... 101
    5.3.1.1 Comparison Between Untreated and Treated, Ungrounded Copper Plates Under Crystallization Fouling Conditions .............................. 102
5.3.1.2 Comparison Between Untreated and Treated, Grounded Copper Plates Under Crystallization fouling Conditions ................................................................. 105

5.3.1.3 Comparison Between Untreated and Treated, Grounded and Ungrounded Stainless Steel Plates Under Crystallization Fouling Conditions ....................................................................................................................... 108

5.3.2 The Studies of The Effects of Electrostatic Water Treatment on Particulate Fouling Deposit and Removal From Stainless Steel Plates .......................... 112

5.3.2.1 Comparison Between Untreated and Treated, Grounded and Ungrounded Stainless Steel Plates Under Particulate Fouling Conditions.. 113

5.3.2.2 The Effects of Electrostatic Water Treatment on the Removal of Calcium Carbonate Particulate Scale Deposition on Stainless Steel Plates . 117

5.4 Conclusions on the Effects of Electrostatic Water Treatment on Scale Growth and Removal ................................................................................................................................. 120

CHAPTER 6: Experimental Studies on the Effects of Electrostatic Water Treatment on Calcium Carbonate Particle Size ................................................. 125

6.1 Description of Test Apparatus ........................................................................................................................................................................................ 125

6.2 Test Method ............................................................................................................................................................................................... 128

6.2.1 Addition of Calcium Carbonate ............................................................................................................................................................................. 128

6.2.2 Particle Size Measurement ................................................................................................................................................................................ 129

6.2.3 Cleaning the System ......................................................................................................................................................................................... 129

6.3 Results ........................................................................................................................................................................................................ 130

6.4 Conclusions on the Effects of Electrostatic Water Treatment on Calcium Carbonate Particle Size ................................................................................................................................. 132

CHAPTER 7: Experimental Studies on the Effects of Electrostatic Water Treatment on Bacterial Growth ................................................................................................................................. 133

7.1 Description of the Test Apparatus' .................................................................................................................................................................................. 133

7.1.1 Components of Simulated Industrial Test Apparatus ................. 135

7.1.2 Components of the Controlled Test Apparatus ................................................. 136

7.2 Test Method ............................................................................................................................................................................................... 137

7.2.1 Preparation and Testing Methods for the Industrial Test System........ 137

7.2.2 Preparation and Testing Methods for the Controlled Test System ... 138

7.2.2.1 Preparation of the Nutrient Broth ............................................................................................................................................................................. 138

7.2.2.2 Preparation of the Agar ......................................................................................................................................................................................... 139

7.2.2.3 Preparation of the Test Cell ................................................................................................................................................................................ 139

7.2.2.4 Preparation of Dilution Test Tubes ........................................................................................................................................................................... 140

7.2.2.5 Collection of Bacteria ......................................................................................................................................................................................... 140

7.2.2.6 Starting the Test ......................................................................................................................................................................................... 140

7.2.2.7 Collection of Data ......................................................................................................................................................................................... 141

7.2.3 Cleaning of the Experimental Systems ................................................. 142
7.3 Results

7.3.1 Comparison Between Treated and Untreated Bacteria Levels in Simulated Industrial Test System

7.3.2 Comparison Between Treated and Untreated Bacteria Levels in Simulated Industrial Test System

7.4 Conclusions on the Effects of Electrostatic Water Treatment on the Simulated Industrial Test and the Controlled Test

CHAPTER 8: Conclusions and Recommendations

8.1 Conclusions

8.2 Recommendations

REFERENCES
LIST OF TABLES

Table 2-1 Thermal Conductivities of Common Heat Exchanger Materials [29]........ 25
Table 4-1 The relative permittivity for various common substances at room temperature [76]. .......................................................... 65
Table 4-2 The conductivity for various common substances at room temperature [76] ................................. 66
Table 4-3 Electric field strength for parallel plate geometry at various voltages..... 68
Table 4-4 Electric Field at time t = 0 in a Series Lossy Capacitor at various voltages and constant thickness............................................. 74
Table 4-5 Electric Field at time t = ∞ in Series Lossy Capacitor at various voltages and constant thickness' ............................................. 76
Table 4-6 Comparison of Electric Field at Multiple Locations in a Parallel Plate Lossy Media to that of Cylindrical Geometry (30,000 V Supply)........ 84
Table 4-7 Comparison of Electric Field at Multiple Locations in a Parallel Plate Lossy Media to that of Cylindrical Geometry (25,000 V Supply)........ 85
Table 4-8 Comparison of Electric Field at Multiple Locations in a Parallel Plate Lossy Media to that of Cylindrical Geometry (20,000 V Supply)........ 85
Table 4-9 Comparison of Electric Field at Multiple Locations in a Parallel Plate Lossy Media to that of Cylindrical Geometry (10,000 V Supply)........ 85
Table 5-1 Typical chemistry levels for the preparation of crystallization fouling .... 94
Table 5-2 Typical chemistry levels for the preparation of crystallization fouling with the addition of Na₂CO₃ ................................................. 96
Table 5-3 Typical chemistry levels for the preparation of particulate fouling ........ 98
Table 5-4 Comparison of average LSI and average deposited mass for untreated and treated, ungrounded copper plates under crystallization fouling conditions .... 121
Table 5-5 Comparison of average LSI and average deposition mass for untreated and treated, grounded copper plates under crystallization fouling conditions ...... 122
Table 5-6 Comparison of average LSI and average deposition mass for untreated and treated, grounded and ungrounded stainless steel plates under crystallization fouling conditions .................................................. 123
Table 5-7 Comparison of average LSI and average deposition mass for untreated and treated, grounded and ungrounded stainless steel plates under particulate fouling conditions .......................................................... 123
Table 5-8 Comparison of pre-fouled and blank stainless steel plates to measure the levels of calcium carbonate removal or deposition under treated and crystallization fouling conditions ................................................. 124
Table 6-1 Calcium carbonate particle size for test #1........................................ 130
Table 6-2 Calcium carbonate particle size for untreated test #2......................... 131
Table 6-3 Calcium carbonate particle size for treated test #3............................. 131
Table 7-1 Comparison of average coliform count and pH for treated and untreated conditions

Table 7-2 Comparison of average TPC count and pH for treated and untreated conditions
LIST OF FIGURES

Figure 1-1 Thesis Outline .................................................................................................................. 6
Figure 2-1 Solubility of Salts in a Heat Exchanger Application ..................................................... 10
Figure 2-2 Effect of Particle size on Deposition [16] .................................................................. 16
Figure 2-3 Diagram of Colloid Double Layer ................................................................................. 18
Figure 2-4 Energy Barrier for Particles Dispersed in a Media ....................................................... 20
Figure 2-5 Parallel Plate Heat Exchanger with no Fouling ............................................................... 23
Figure 2-6 Parallel Plate Heat Exchanger with Fouling ................................................................. 24
Figure 2-7 Solubility of Calcium Carbonate in Water in Contact With Ordinary Air [37] .............. 33
Figure 2-8 Solubility of Calcium Carbonate in Tap Water at 30°C as a Function of pH [10] ........... 34
Figure 2-9 Solubility of Calcium ion (Ca\(^{2+}\)) in Water at 16°C in Contact With CO\(_2\) at Low and High Partial Pressure[37]. .......................................................... 35
Figure 2-10 Solubility-Super-Solubility Diagram [10] .................................................................. 36
Figure 2-11 (a) SEM Image of Hexagonal Calcite Crystalline Structure at 200 \(\mu\)m Magnification. SEM Image of Cubic Calcite Crystalline Structure ........................................... 39
Figure 2-12 SEM Image of Aragonite Crystalline Structure at 10 \(\mu\)m Magnification ...................... 40
Figure 2-13 SEM Image of Vaterite Crystalline Structure ............................................................. 41
Figure 3-1 Schematic Diagram of the Operation of an electronic ant-fouling unit. Provided by Drexel University [10] ............................................................................................................. 50
Figure 3-2 Schematic Diagram of Electrostatic Water Treatment Device in a Pipe Bend .............. 54
Figure 3-3 Schematic Diagram of Electrostatic Water Treatment Device in a Side Steam Reaction Chamber ........................................................................................................................................ 54
Figure 3-4 Construction of Electrostatic Rod ................................................................................... 55
Figure 3-5 Schematic of Electrostatic Water Treatment Device used at Lehigh University .......... 56
Figure 4-1 Parallel Plate Geometry ................................................................................................ 67
Figure 4-2 Cylindrical Electrode Geometry ..................................................................................... 69
Figure 4-3 Electric field strength for cylindrical electrode geometry at various applied voltage levels .................................................................................................................................................................. 70
Figure 4-4 Circuit diagram of series lossy capacitor ....................................................................... 72
Figure 4-5 Parallel plate series lossy capacitor at time \(t = 0\) .......................................................... 73
Figure 4-6 Parallel plate series lossy capacitor at time \(t = \infty\) ......................................................... 75
Figure 4-7 Cylindrical series lossy capacitor at time \(t = 0\) ............................................................ 77
Figure 4-8 Electric field in dielectric material at Time \(t = 0\) .......................................................... 79
Figure 4-9 Electric Field in Water at Time \(t = 0\) ............................................................................ 80
Figure 4-10 Cylindrical series lossy capacitor at time \(t = \infty\) ......................................................... 81
Figure 4-11 Electric field in dielectric material at Time $t = \infty$ ........................................ 83
Figure 4-12 Electric Field in Cooling Water at Time $t = \infty$ ........................................ 83
Figure 5-1 Test apparatus built at Lehigh University to measure the effects of
electrostatic water treatment on the effects of calcium carbonated deposition .......................... 88
Figure 5-2 Schematic of parallel-flow, plate heat exchanger .............................................. 89
Figure 5-3 The calculated LSI for the untreated and treated ungrounded copper systems ................................................................. 103
Figure 5-4 Comparison of calcium carbonate scale deposition by mass for treated and
untreated plates ........................................................................................................ 104
Figure 5-5 100X magnification and full view of untreated, ungrounded copper plates ................................................................. 104
Figure 5-6 100X magnification and full view of treated, ungrounded copper plates 105
Figure 5-7 The calculated LSI for the untreated and treated copper grounded systems ................................................................. 106
Figure 5-8 Comparison of calcium carbonate crystallization scale deposition by mass for treated and untreated copper plates ................................................................. 107
Figure 5-9 100X magnification and full view of untreated grounded copper plate under crystallization fouling ................................................................. 108
Figure 5-10 100X magnification and full view of treated grounded copper plate under crystallization fouling ................................................................. 108
Figure 5-11 The calculated LSI for the untreated and treated grounded and
ungrounded stainless steel systems with crystallization fouling ................................................................. 110
Figure 5-12 Comparison of calcium carbonate crystallization scale deposition by mass for treated and untreated stainless steel plates ................................................................. 111
Figure 5-13 Full view and close-up view of untreated, ungrounded stainless steel plate under crystallization fouling ................................................................. 112
Figure 5-14 Full view and close-up view of treated, grounded stainless steel plate under crystallization fouling ................................................................. 112
Figure 5-15 The calculated LSI for the untreated and treated grounded and
ungrounded stainless steel systems under particulate fouling conditions ................................................................. 114
Figure 5-16 Comparison of calcium carbonate particulate scale deposition by mass for treated and untreated stainless steel plates ................................................................. 115
Figure 5-17 Full view and close-up view of untreated, ungrounded stainless steel plate under particulate fouling ................................................................. 116
Figure 5-18 Full view and close-up view of treated, ungrounded stainless steel plate under particulate fouling ................................................................. 116
Figure 5-19 The calculated LSI for treated grounded and ungrounded stainless steel plates under crystallization fouling conditions ................................................................. 118
Figure 5-20 Levels of calcium carbonate scale removal or deposit from or on stainless steel plates under crystallization fouling conditions ................................................................. 119
Figure 5-21 Full view and close-up view of grounded and treated plate 1 for
measurement of the effects of electrostatic water treatment on calcium carbonate removal ................................................................. 120
Figure 6-1 Test apparatus built to analyze the effects of electrostatic water treatment on calcium carbonate particle size ............................................................ 126
Figure 6-2 Top view of piping system in the bottom of the sump......................... 127
Figure 7-1 First test apparatus built at Lehigh University to measure the effects of electrostatic water treatment on the effects of bacteria in simulated industrial environment ............................................................................. 134
Figure 7-2 Second test apparatus built at Lehigh University to measure the effects of electrostatic water treatment on the effects of bacteria in a controlled environment .................................................................................. 135
Figure 7-3 The Dilution Process for Preparing Plates Counts................................. 141
Figure 7-4 Coliform CFU per 100 ml of water and pH levels for a treated simulated industrial system ................................................................. 144
Figure 7-5 Coliform CFU per 100 ml of water an pH levels for an untreated simulated industrial system ................................................................. 144
Figure 7-6 Coliform CFU 100 per ml of water for a treated and untreated simulated industrial system .................................................. 145
Figure 7-7 Total plate count (TPC) per ml of water for a treated and untreated simulated industrial system ................................................................. 146
Figure 7-8 pH for a treated and untreated simulated industrial system ............. 147
Figure 7-9 Colony forming units per ml of water for the treated controlled test.... 148
ABSTRACT

The electrostatic water treatment technology explored utilizes electrostatic fields to replace chemical water treatment in industrial HVAC systems. In order to evaluate the effectiveness of electrostatic water treatment, several issues were explored during this investigation.

The first study focused on an analysis of the cylindrical geometry prevalent in existing electrostatic water treatment systems. The electric field strengths were compared for various applied voltage levels.

This was followed by a study on the effects of electrostatic water treatment on calcium carbonate deposition. For the parameters of studied it was found that electrostatic water treatment may have decreased the calcium carbonate deposition by 16.55 percent on grounded and ungrounded stainless steel plates under crystallization fouling conditions. Under the particulate fouling and the specific electrostatic treatment conditions applied, very little to no effect was observed.

Studies were also completed on the effects of electrostatic water treatment on calcium carbonate particle size. The results observed suggest that electrostatic water treatment may inhibit the agglomeration of calcium carbonate particles in water.

This was followed-up by a study of the direct effects of electrostatic field exposure on coliform, total planktonic bacteria and pseudomonas aeruginosa. Tests were completed with a control system and a treated system. The bacterial levels in the control system and the treated system were compared and the effectiveness of
electric fields on bacteria growth was evaluated. It was concluded that electrostatic water treatment as currently applied has little to no effect on bacterial growth. Overall, the study shed some useful light into the promising and yet complex area of electrostatic water treatment.
1.1 Water Treatment and Fouling Background

The build up of scale deposits is a very common problem found in many industrial applications that utilize natural water supplies. One of the most common types of scaling deposits is found in the form of calcium carbonate or CaCO$_3$. Calcium carbonate occurs naturally in water and is ordinarily found in the form of chalk, limestone and marble. Calcium carbonate is unique in the sense that it has an inverse solubility, while most salts such as NaCl and CaCl increase in solubility as temperature increases, CaCO$_3$ decreases in solubility as temperature increases. This characteristic of CaCO$_3$ subsequently creates problems in heat exchanger applications. The build up of this CaCO$_3$ scale is typically known as fouling.

Fouling in heat exchangers will reduce the heat transfer efficiencies and if allowed to grow thick enough it can even create huge pressure drops through systems. In the U.K. alone the formation of scales in industrial processes is estimated to cost £1 billion per year [1]. These costs can be attributed to cleaning (i.e. descaling) and the poor thermal conductivity of scaled surfaces. It has also been found that heat transfer can be decreased by as much as 95% by a CaCO$_3$ scale layer only 25 mm thick [2]. As can be seen, a reduction of calcium carbonate scaling would greatly benefit industrial systems that utilize natural water sources.
1.1.1 Chemical Solutions to Fouling Background

Fouling and therefore methods to reduce fouling have been around since the early days of recirculating cooling water systems (since the late 1930’s and early 1940’s) [3]. The majority of treatments since the 1930’s have been based on the addition of chemicals to inhibit and remove scale from pipe walls. Some of these chemicals include, sulfuric acid, chlorine, silicates, polyphosphates and chromates. The sales of traditional water treatment chemicals and services in the United States alone, (the worlds largest water treatment market) is worth about $3 billion a year and grows at an annual rate of about 3%. Chemical sales world wide for water treatment are worth about $7 billion dollars a year [3]. Traditional chemical treatment is a recurring process and thus results in an expensive means to treat industrial systems. The addition of chemicals such as sulfuric acid, chromate and chlorine also raise environmental hazard concerns.

1.1.2 Electrostatic Water Treatment

Due to the high cost of traditional chemical treatment there have been many developments related to cheaper and less hazardous means to treat industrial systems. One of the developments has been in electrostatic water treatment. This type of treatment distributes an electric field at critical predetermined locations in an industrial system. As a result of this electric field, electrostatic water treatment has claimed to eliminate pre-existing calcium carbonate scale and prevent further deposition of calcium carbonate on surfaces of industrial systems. Electrostatic water treatment uses very little power (on the order of 2-3 watts), provides continuous
treatment and does not have any environmental side effects. Although the benefits seem limitless with electrostatic water treatment, very little is known about the mechanics and the effectiveness of this particular type of water treatment.

1.2 Objective of the Present Investigation

The objective of the present study was to determine the effectiveness of electrostatic water treatment and its applications to calcium carbonate scale removal, prevention of calcium carbonate formation, calcium carbonate particle agglomeration and bacteriological growth. The scope of the research also included the development of an understanding of the electric field generated by electrostatic water treatment devices.

1.3 Thesis Structure

The structure of the present thesis can be seen in Figure 1-1. Chapter 2 provides a general review of the different types of fouling. In addition, this chapter contains a more in-depth analysis of the mechanism of fouling. This is then followed by an evaluation of the thermal and pressure efficiency losses due to fouling. In Chapter 2 we will also examine the varying models that attempt to simulate the rate and level of fouling. We will then focus our review on the fouling of calcium carbonate and the effects of pH, pressure and temperature on this particular type of fouling. We will conclude Chapter 2 with a description of the different types of calcium carbonate scale.
In Chapter 3 we will study natural, traditional and non-traditional methods to prevent calcium carbonate scale. Chapter 3 will begin with a description of natural inhibitors to calcium carbonate scale. This will be followed by a review of the traditional chemical treatment processes that have been used since the 1930’s and
1940's. After chemical treatment has been reviewed we will delve into the more recent non-traditional water treatment devices. This review will begin with a study of the non-traditional chemical treatment such as ion exchange and ozonation. We will then study the non-chemical non-traditional forms of water treatment such as magnetic and electromagnetic water treatment. Chapter 3 will conclude with an in depth review of electrostatic water treatment.

In order to obtain a better understanding of the electric field generated by electrostatic water treatment devices we will complete a rigorous study of the electric fields for multiple geometries in Chapter 4. We will study the electric fields generated by parallel plates and cylindrical geometries for a single media and for multiple media in series. We will complete this chapter with a comparison of the electric field strength for all the geometries reviewed in Chapter 4.

Chapter 5 gives a detailed description of the experimental apparatus and method for measuring the effects of electrostatic water treatment on calcium carbonate scale growth and removal. The results to these experiments will also be given in this chapter.

Chapter 6 will review the effects of electrostatic fields on the calcium carbonate particle agglomeration. A complete description of the experimental apparatus and method for measuring calcium carbonate particle agglomeration will be given in this chapter.
Chapter 7 will give a thorough description of the experimental apparatus and test method for observing the effects of electrostatic water treatment and its effects on bacterial growth. A complete analysis of the results will conclude this chapter.

Finally, Chapter 8 will summarize the results and conclusions found in Chapters 5, 6 and 7.
CHAPTER 2: A Review of Fouling

Fouling can be described as the deposition of undesirable materials that produce dirty and inefficient heating and cooling systems, impeding the flow of heating and cooling water. It involves the physical adherence to surfaces and agglomeration of insoluble salts, corrosion products, sediment, air-blown debris and biological growth [3]. We are most typically concerned with the fouling of calcium carbonate on heat exchanger systems. Fouling can significantly reduce the thermal efficiency of a heat exchanger system and in some cases can cause a catastrophic failure. It is generally recognized in the industry that fouling has a decisive effect on both initial design considerations and the operation of heat transfer equipment [4].

2.1 Types of Fouling

Fouling can be classified into the following six broad types: 1) precipitation or crystallization fouling, 2) particulate fouling, 3) chemical reaction fouling, 4) corrosion fouling, 5) biological fouling and 6) freezing fouling [4]. It is possible for one or more of these types of fouling to occur in a system simultaneously. All of these types of fouling will be discussed in detail.

2.1.1 Crystallization or Precipitation Fouling

Crystallization fouling refers to the crystalline growth of a variety of insoluble salts due to solubility changes with temperature. Inverse solubility salts; such as, CaCO₃, CaSO₄, and Na₂SO₄, become less soluble as temperature is raised and
therefore crystallize on the cold water side on the heated plate. Whereas, normal solubility salts such as NaCl and MgSO4 would form scales on the hot water side on the cooled plate [5,6,7]. An inverse soluble salt such as CaCO3, when dissolved in water will exist as ions. One ion will be Ca2+(Calcium) and the other ion will be CO32-(Carbonate). As temperature is raised the solubility will decrease and some of the ions will crystallize to form CaCO3. An explanation of the phenomenon that occurs with inverse and normal solubility salts on heat exchanger surfaces can be seen in Figure 2-1. The hot water is transferring heat to the cold water and the water temperatures come to an equilibrium. As seen, CaCO3 becomes less soluble as the local water temperature increases and MgSO4 becomes less soluble as the local water temperature decreases.

Figure 2-1 Solubility of Salts in a Heat Exchanger Application
Crystallization fouling can also form when the concentration of a solution is raised due to evaporation. Such a case would occur in a cooling tower where water is evaporated and the concentration of ions is increased.

2.1.2 Particulate or Sludge Fouling

Particulate or sludge fouling is a term used to describe the soft deposits or water based suspensions of mud, clays, sand, silt, colloids, biomass, oil, and precipitated salts in an amorphous form [3,8,9]. Particulate fouling usually occurs in a low-flow area such as heat exchangers, pipe bends or cooling tower sumps. Particulate fouling can and will reduce heat transfer efficiencies. Most particulate fouling can be attributed to air-blown leaves, sand and dirt. In other cases, particulate fouling can occur when the salts in the bulk water become supersaturated. The result is the precipitation of these salts onto low-flow areas.

2.1.3 Chemical Reaction Fouling

Chemical reaction fouling involves deposits caused by some form of chemical reaction within a fluid stream (rather than the heat transfer surface). Chemical reaction fouling can occur under the influence of the temperature present in heat exchangers, namely auto-oxidation, cracking and polymerization of hydrocarbons [10].

2.1.4 Corrosion Fouling

Corrosion fouling involves a chemical reaction between a heat transfer surface and fluid stream, producing corrosion products, which, in turn, foul the surface.
Corrosion is often accelerated by the presence of other deposits, which would be called under-deposit corrosion. An example of this would be an aqueous process often experienced in waste heat boilers [10].

2.1.5 Biological Fouling

Open re-circulating cooling systems are continually subject to contamination by the introduction of a wide variety of microbiological organisms such as bacteria, fungi, and algae. Biofouling, with its physical adherence to heat exchangers and other surfaces, is a major cause of cooling system deterioration and loss of efficiency [3,11]. The microorganisms, which cause fouling, can be categorized into two types, planktonic and sessile. Planktonic organisms are the aggregate of passively floating microorganisms floating in an industrial system. Sessile organisms are microorganisms that are permanently attached to a pipe wall. Sessile organisms are the prime contributor to the production of biofilm. Biofilm is a form of biofouling, whereby alga or bacteria adhere to wet cooling water system surfaces.

Microorganisms of bacteria, in particular, can be classified into two forms, aerobic and anaerobic. Aerobic refers to the types of bacteria which need oxygen to sustain life. Anaerobic refers to the types of bacteria which do not need to sustain life. The most prolific biofilm formers in cooling systems are the aerobic strains of bacteria. Some of the bacteria in this category include: pseudomonas aeruginosa, aerobacter, bacillus, flavobacterium and proteus vulgaris.
2.1.6 Freezing Fouling

Freezing fouling occurs as a result of the solidification of a pure liquid or one component from a liquid phase on a sub-cooled heat transfer surface. This fouling is similar to precipitation fouling but it does not have the diffusion mechanism [10].

2.2 The Complete Process of Fouling

The fouling process and the causes of scaling vary from case to case and are extremely complex. Over the years a number of researchers have studied the mechanism of scale formation in an effort to develop methods to better control scaling problems [10]. The life cycle and formation of scale can be classified into five successive events. The first being initiation (delay, nucleation, induction, incubation, surface conditioning), followed by transport (mass transfer), attachment (surface integration, sticking, adhesion, bonding), removal (release, reentrainment, detachment, erosion, shedding), and finally aging [12].

2.2.1 Initiation Process

The initiation process is associated with a delay period that is observed before any significant fouling is noticed in an experiment or on a heat transfer surface [12]. The delay period can be denoted by $\Theta_D$. For crystallization and chemical reaction fouling the delay period is closely associated with the nucleation of particles on the heat transfer surface. For this reason $\Theta_D$ tends to decrease as the level of supersaturation is increased. For salts such as CaCO$_3$, the level of saturation is increased as temperature increases and thus for CaCO$_3$, $\Theta_D$ will decrease as the heat transfer
surface temperature increases. The effect of velocity on the delay period is still in doubt [13]. For particulate fouling there is no delay period.

For nucleation to occur in crystallization fouling, a certain number of molecules must agglomerate and then orient themselves in a fixed lattice. It is believed that the molecules grow into oriented clusters or layers in a molecule-by-molecule reaction. The first layer is formed directly on the surface. Therefore, the delay period will decrease as the surface roughness increases. The roughness projections provide sites for nucleation and the surface grooves provide regions for deposition that are sheltered from the mainstream.

The total crystallization rate will depend on several variables, which include; the degree of super-saturation, delay time, type of scale-causing materials, number of nucleation sites, temperature, pressure, pH, agitation and other environmental factors [14].

2.2.2 Transport Process

Transport is the best understood of the fouling stages. To form a deposit on a heat transfer surface, fouling species must continually be transported from the bulk fluid to the heat transfer surface [10,12]. In a heat affected zone there exists a concentration gradient of ions, molecules and or sub-micron particles that will be transported from the bulk water to the heat transfer surface. The concentration of these particles in the bulk water will be denoted by \( C_b \) (kg/m\(^3\)), and the concentration at the heat transfer surface will be denoted by \( C_s \) (kg/m\(^3\)).
Knowing these concentrations can give us an idea of the local deposition rate given as:

\[ m = k_t (C_b - C_s) \]  

(2.1)

where \( k_t \) is the transfer coefficient (m/s). In the case of ions, molecules and sub-micrometer particles it is equivalent to the mass transfer coefficient \( k_m \). The value of \( k_m \) can be obtained using the following equation [10]:

\[ Sh = a(Re)^n (Sc)^m \]  

(2.2)

where:

- \( Sh \) = Sherwood number \( (k_m d / D) \)
- \( Re \) = Reynolds number \( (\rho u d / \mu) \)
- \( S \) = Schmidt number \( (\mu / \rho D) \)
- \( \rho \) = Fluid density \( (kg/m^3) \)
- \( \mu \) = Fluid viscosity \( (kg/m \cdot s) \)
- \( d \) = Characteristic length (e.g. pipe diameter)
- \( a \) = Constant
- \( m, n \) = Numerical indices

For a dilute suspension of spherical particles, the Brownian diffusivity \( D \) is given by the Stokes-Einstein equation [15]:

\[ D = \frac{k_BT}{3\pi \eta d} \]  

(2.3)
where:

\[ k_B = \text{Boltzmann's constant (1.38 \times 10^{-23} \text{ J/K})} \]
\[ T = \text{Fluid temperature (K)} \]
\[ d_p = \text{Particle diameter (m)} \]

**Figure 2-2 Effect of Particle size on Deposition [16]**

Beal [16] formulated a graphical representation for determining the value of \( k_m \) as seen in Figure 2-2. Starting at the left of the graph, the deposition of particles is very small and is entirely diffusion controlled. Notice the rate decreases as particle size increases since the Brownian diffusion coefficient is inversely proportional to the size of the particles. At some point the momentum of the particle plays a larger role
than the Brownian movement. At this point the deposition becomes essentially momentum controlled. Proceeding to the right at some point the particle size has increased to where the size has no effect on the boundary layer thickness. At this point the value of $k_m$ remains constant.

2.2.3 Attachment Process

Attachment of the particle to the wall involves the transport of the key components to the location where the solid deposit scale will actually be formed. This is not the case for particulate fouling since the particle was formed in the bulk of the system. Generally, there are a few forces that will attach a particle once it gets close to a surface. Depending on the particle size and its nature the attractive forces can be Van Der Waals Forces or Electrostatic Double Layer Forces.

2.2.3.1 Van Der Waals Forces

Particles with a diameter of 50 μm and below will be affected by attractive Van Der Waals forces during the attachment process [10]. The following equation was introduced by Hamaker to describe the Van Der Waals forces ($F_w$) generated by a sphere resting on a flat plate:

$$F_w = \frac{A_h r}{6x^2} \quad (2-4)$$

where:

$A_h$ = Hamaker constant  
$r$ = Radius of the sphere  
$X$ = Separation distance between the sphere and the Plate
This equation can be used to account for the interaction between atoms and molecules [17,18].

2.2.3.2 Double Layer Force and Zeta Potential

The double layer is used to describe the ionic layers that form when a charged particle is immersed in a media. For our case we will study the double layers on colloids and metal surfaces. When a negatively charged metal surface or a colloid is immersed in water it will tend to attract positive ions, also called counter-ions. This initial strong attraction will attract counter-ions and form the Stern Layer seen in Figure 2-3.

![Figure 2-3 Diagram of Colloid Double Layer.](image)

After the Stern Layer forms, negative ions, also called co-ions, are still repelled by the negative inner charge and counter-ions are still attracted. The initial attraction of positive ions is high but as the layer thickens and the negative inner
charge is neutralized the concentration of negative ions begins to increase. This mixed layer can be described as the Diffuse Layer and can also be seen in Figure 2-3. The Diffuse Layers ends when the concentration of positive ions and negative ions is equal [19,20,21]. The combination of the Stern layer and the Diffuse Layer is what we define as the Double Layer.

The combination of the negatively charged particle and the Double Layer will generate a potential difference. This electrokinetic potential at the surface of the particle is generally referred to as the surface potential and is on the order of millivolts. When we measure the potential of a charged particle we find that it will be highest in the Stern Layer and then will drop exponentially as we pass through the Diffuse Layer. The potential can be measured anywhere through these regions but generally the particles in the Diffuse Layer are loosely attached so we measure in a region in between the Stern Layer and the Diffuse Layer. The potential measured in this region is called the zeta potential. Zeta potential can be measured by placing charged particles in an electric field and measuring the velocity at which they migrate through this field.

Particles of similar surface charge in a system will have a natural tendency to repel each other. The result will be that the particles will not agglomerate and form larger colloids.

2.2.3.3 Balance Between Van der Waals and Electrostatic Repulsion Forces

As we have mentioned earlier, Van der Waals forces are attractive forces by nature and particles of similar charge are repulsive. Naturally, there will exist a
balance between when two particles will tend to agglomerate or remain dispersed. The energy balance between these two opposing forces on particles can be seen in Figure 2-4.

In order for two particles to agglomerate they must overcome the repulsive energy barrier as they approach each other as seen in Figure 2-4. This can only be accomplished if there is enough kinetic energy to "jump over" this barrier. This kinetic energy would be in the forms of mass and velocity. Once the barrier is "jumped" the particles will agglomerate. The height of the energy barrier can change, depending on the pH, ionic environment, or by adding surface active materials to affect the charge on the particles. Whatever the change may be, zeta potential can indicate the impact of the alteration to the overall stability of the system [19].

Figure 2-4 Energy Barrier for Particles Dispersed in a Media.
2.2.4 Removal Process

The removal of fouling material may begin as soon as the initial layer is deposited [22]. The removal of fouling usually occurs as a result of dissolution or erosion. Fouling removal models are generally based on the mechanism of erosion and it is generally accepted that the removal rate is directly proportional to the deposit thickness and the shear stress exerted by the fluid on the surface and inversely proportional to the strength of the deposit [10,23,24]. Other more advanced models examine the structure and properties of deposits and their complex interaction with the growth process in a hydrodynamic field [10,25].

2.2.5 Aging Process

The aging process of fouling also starts as soon as it is laid down on a heat transfer surface. The aging process can include a change in the crystalline structure of scale deposits. In addition, as the scale increases in thickness in the presence of a constant heat flux, the temperature of the deposit will increase and the scale structure will be further strengthened. At the same time however, the thermal stresses created in this case could weaken the bond of the scale and hydrodynamic forces could wash the deposit away [12].

2.3 Efficiency Effects of Fouling

Fouling can affect the efficiency of a system in two major ways. The first and most obvious affect is the thermal efficiency drop. Many scales such as CaCO$_3$ have a very low thermal conductivity, even a thin layer of CaCO$_3$, therefore, will greatly
drop the thermal efficiency of a heat exchanger. The second less obvious result is the pressure drop in a system as fouling build up increases. As fouling increases, pipe diameters will decrease, thus restricting the flow of water. As a result pumps will have to work harder to maintain the same flow rates. In some cases heat exchangers can fail due to the increased pressure drops [26,27].

2.3.1 Thermal Efficiency in Fouling Conditions

In order to further understand the decrease in thermal efficiency when fouling is introduced to a heat exchanger system, we will study a parallel plate heat exchanger with and without fouling as seen in Figure 2-5 and Figure 2-6. For a system that does not have any fouling there are three sections of concern. The two outer sections, labeled hot and cold fluid, are primarily governed by thermal convection. Section B, which is our thermally conducting media, is primarily governed by thermal conduction. The overall heat transfer coefficient $U$ will be as follows [28]:

$$U = \frac{1}{\left[\frac{1}{h_H} + \left(\frac{L_A}{k_A}\right) + \left(\frac{1}{h_C}\right)\right]}$$  \hspace{1cm} (2-5)

where:

- $T_{CF}, T_{HF}$ = Temperature of the cold and hot stream
- $h_{CF}, h_{HF}$ = Convection heat transfer coefficients of the cold and hot stream
- $k_B$ = Thermal conductivity of the conducting media B
- $L_B$ = Thickness of the conducting media B
For a system that has been fouled, the overall heat transfer coefficient will decrease significantly due to the decrease in thermal conductivity provided by the fouling material. Sections A and C will be fouling material and will generally have a lower conductivity than the conducting section B. Sections A, B and C are governed primarily by thermal conductivity. The two outer sections, labeled hot and cold fluid, will be governed primarily by thermal convection. The overall heat transfer coefficient for this case will be given as:

\[
U = \frac{1}{\left[\frac{1}{h_{HF}} + \left(\frac{L_A}{k_A}\right) + \left(\frac{L_B}{k_B}\right) + \left(\frac{L_C}{k_C}\right) + \left(\frac{1}{h_{CF}}\right)\right]}
\]  

(2-6)
For a system that has been fouled, the overall heat transfer coefficient will decrease significantly due to the decrease in thermal conductivity provided by the fouling material. Sections A and C will be fouling material and will generally have a lower conductivity than the conducting section B. Sections A, B and C are governed primarily by thermal conductivity. The two outer sections, labeled hot and cold fluid, will be governed primarily by thermal convection. The overall heat transfer coefficient for this case will be given as:

\[
U = \frac{1}{\left(\frac{1}{h_{HF}} + \frac{L_A}{k_A} + \frac{L_B}{k_B} + \frac{L_C}{k_C} + \frac{1}{h_{CF}}\right)}
\]  

(2-6)
where:

\[ T_{CF}, T_{HF} \] = Temperature of the cold and hot stream.

\[ h_{CF}, h_{HF} \] = Convection heat transfer coefficients of the cold and hot stream.

\[ k_A, k_B, k_C \] = Thermal conductivities of the conducting media B and length of fouling deposits A and C.

\[ L_A, L_B, L_C \] = Length of the conducting media B and length of fouling deposits A and C.

Figure 2-6 Parallel Plate Heat Exchanger with Fouling

By observing the differences between the un-fouled and fouled overall heat transfer coefficient, one can conclude that the fouled condition will have a smaller coefficient given that the stream temperatures and the conducting media remain constant. Table 2-1 refers to some common thermal conductivities used in fouled and
where:

\[ T_{CF}, T_{HF} = \] Temperature of the cold and hot stream.
\[ h_{CF}, h_{HF} = \] Convection heat transfer coefficients of the cold and hot stream
\[ k_A, k_B, k_C = \] Thermal conductivities of the conducting media B and length of fouling deposits A and C.
\[ L_A, L_B, L_C = \] Length of the conducting media B and length of fouling deposits A and C.

Figure 2-6 Parallel Plate Heat Exchanger with Fouling

By observing the differences between the un-fouled and fouled overall heat transfer coefficient, one can conclude that the fouled condition will have a smaller coefficient given that the stream temperatures and the conducting media remain constant. Table 2-1 refers to some common thermal conductivities used in fouled and
un-fouled heat exchangers. Notice that a layer of calcium carbonate can be over 400 times less conductive than a layer of copper of the same thickness.

Table 2-1 Thermal Conductivities of Common Heat Exchanger Materials [29]

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity (W/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium Carbonate</td>
<td>.9 - 2.9</td>
</tr>
<tr>
<td>Calcium Phosphate</td>
<td>2.6</td>
</tr>
<tr>
<td>Calcium Sulphate</td>
<td>.8 - 2.3</td>
</tr>
<tr>
<td>Magnetite Iron Oxide</td>
<td>2.9</td>
</tr>
<tr>
<td>Silicate Scale</td>
<td>.08 - .13</td>
</tr>
<tr>
<td>Biofilm</td>
<td>0.7</td>
</tr>
<tr>
<td>Copper</td>
<td>400</td>
</tr>
<tr>
<td>Mild Steel</td>
<td>27.6</td>
</tr>
</tbody>
</table>

2.3.2 Pressure Drop Due to Fouling

For fluid flow in pipes, there exists a pressure drop due to frictional forces. The amount of pressure drop will be dependent upon a number of factors that include; fluid viscosity (µ), experimentally determined frictional factor (f), length of the section (L), pipe diameter (D) and fluid volumetric flow (Q). The pressure drop ΔP will be as follows [30]:

\[
\Delta P = \frac{8\mu f Q^2}{\pi^2 D^5}
\]  

(2-7)

As can be seen, a slight decrease in the tube diameter due to fouling will cause a significant increase in the pressure drop across a tube of similar length. It has been stated that more heat exchangers will fail because of an excessive pressure drop, not
because of reduced heat transfer [31]. As mentioned, the friction factor (f), is experimentally determined and is readily available in many fluid mechanics books for various situations.

2.4 Models Used to Simulate The Fouling Process

As can be seen, fouling is a multifaceted six-part process that involves many steps that are difficult to simulate mathematically. Although it is difficult, numerous studies have been conducted to simulate the general process of fouling. These models, if correct, could help to pre-determine high fouling locations in systems that have yet to be built. The general mathematical models for a fouling process have been based on a material balance in a system as seen in Equation 2-8 [22]:

\[
\frac{dR_f}{dt} = \frac{dx_f}{k_f dt} = \Phi_d - \Phi_r
\]

Where \( \frac{dR_f}{dt} \) is the fouling rate, \( \Phi_d \) is the deposition rate, and \( \Phi_r \) is the removal rate.

The deposition rate, \( \Phi_d \) depends on the type of fouling (scale, precipitation and biofouling) and the removal rate, \( \Phi_r \), depends on the bonding force of the fouling and the shear stress on the fouling due to flow velocity in the system [10]. We will introduce two models that have been further developed to simulate the fouling process.
2.4.1 Kern-Seaton Model

The Kern-Seaton Model [22] is one of the simplest models developed to simulate the fouling process. The equation is based on experimental results and is as follows:

\[
R_f = R_f^* \left(1 - e^{-\alpha t} \right) \tag{2-9}
\]

Where \( R_f^* \) is an asymptotic value of the fouling resistance, \( R_f \) and \( \beta \) is a removal rate function.

Kern and Seaton proposed that the deposition rate \( \Phi_d \) would be:

\[
\Phi_d = \frac{1}{k_f} a_1 C \dot{M} \tag{2-10}
\]

and that the removal rate \( \Phi_r \) would be:

\[
\Phi_r = \frac{1}{k_f} a_2 \tau \dot{x}_f \tag{2-11}
\]

where:

- \( x_f \) = Deposit thickness
- \( t \) = time
- \( C \) = Concentration of fouling causing salts
- \( \dot{M} \) = Mass flow rate of solution
- \( k_f \) = Thermal conductivity of fouling material
- \( \tau \) = Shear stress
- \( a_1, a_2 \) = Constants
Using Equations 2-10 and 2-11 in Equation 2-8 and solving for \( x_r, R_f^* \), and \( \beta \), in Equation 2-9 will yield the following:

\[
R_f^* = \frac{a_1CM}{k_f a_2 \tau} \tag{2-12}
\]

and

\[
\beta = a_2 \tau \tag{2-13}
\]

so that:

\[
R_f = \frac{a_1 CM}{k_f a_2 \tau} \left(1 - e^{-\beta} \right) \tag{2-14}
\]

The Kern-Seaton model is essentially a mathematical representation of the experimentally observed asymptotic fouling curve. Although the model does not always agree with actual fouling data, the model is often used because of its simplicity [10]. As seen from Equation 2-14 the Kern-Seaton model assumes that the deposition rate of fouling is proportional to the flow velocity of the solution. However, it has been observed that the deposition rate is actually inversely proportional to flow velocity [8,10,32,33,34]. This leads one to search for a more accurate but possibly more complex representation of fouling.
2.4.2 Watkinson-Epstein Model

Watkinson and Epstein proposed that both the transfer and the adhesion processes are related to the deposition rate of fouling material. The deposition rate can be defined as [10,35]:

\[
\dot{m}_d = k_m S(C_b - C_s)
\]  

(2-15)

where:

\[
\begin{align*}
  k_m &= \text{Mass transfer coefficient} \\
  C_b &= \text{Concentration of species in the bulk} \\
  C_s &= \text{Concentration of the species on the scale}
\end{align*}
\]

and S is defined as the sticking probability:

\[
S = a_3 \frac{\exp\left(\frac{E_{\text{act}}}{R_g T_s}\right)}{fu^2}
\]

(2-16)

where:

\[
\begin{align*}
  a_3 &= \text{Constant} \\
  E_{\text{act}} &= \text{Height of potential energy barrier} \\
  R_g &= \text{Universal gas constant} \\
  T_s &= \text{Surface temperature (K)} \\
  f &= \text{Friction factor} \\
  u &= \text{Flow velocity}
\end{align*}
\]

Equation 2-16 is an Arrhenius-type equation, representing the crystallization rate at a surface.
Watkinson and Epstein also used Equation 2-10 and 2-11 as Kern and Seaton did in order to determine the deposition and removal rates. Using Equation 2-8 they obtained the following equation for \( R_f \):

\[
R_f = a_4 \left( \frac{(C_b - C_s) \exp\left(- \frac{E_{act}}{R_s T_s}\right)}{u^3} \right) \left[1 - \exp\left(- \beta_k\right)\right] \tag{2-16}
\]

As can be seen in this model, the flow velocity is inversely proportional to the fouling resistance.

### 2.5 The Mechanics of Calcium Carbonate Scale Formation

Makeup water in industrial systems is never pure and will always contain many different dissolved salts. The concentration of these dissolved salts will vary with the source of the water. Hard water indicates water that has high levels of dissolved salts and soft water indicates water that has low levels of dissolved salts. Most makeup water will contain varying amounts of calcium carbonate (\( \text{CaCO}_3 \)), which is a major source of many crystalline scales formed in industrial systems. As mentioned earlier, \( \text{CaCO}_3 \) is an inverse soluble salt, in that as temperature rises, calcium carbonate becomes less soluble. Calcium carbonate also decreases in solubility as the pH rises and increases in solubility as the partial pressure of carbon dioxide (\( \text{CO}_3 \)) rises. The mechanics of calcium carbonate scale formation are very complex and the efficiency losses due to it are usually tremendous.
2.5.1 Calcium Carbonate Equilibrium

The chemical equilibrium of calcium carbonate in water is a multi-stage process that can be initiated by adding calcium chloride (CaCl$_2$) and sodium bicarbonate (NaHCO$_3$) to water. The addition of calcium chloride to water will be represented as:

$$CaCl_2(s) \leftrightarrow Ca^{2+}(aq) + Cl^-_2(aq) \quad (2-17)$$

The addition of sodium bicarbonate to water will be represented as:

$$NaHCO_3(s) \leftrightarrow Na^+(aq) + HCO_3^-(aq) \quad (2-18)$$

Where (s) refers to the solid state and (aq) refers to the aqueous state. When we add these in combination to water we create the environment to produce calcium carbonate. The aqueous calcium (Ca$^{2+}$) and aqueous bicarbonate (HCO$_3^-$) will crystallize to form CaCO$_3$ when there is a rise in temperature and/or pH or a decrease in the partial pressure of carbon dioxide. The equilibrium equation will be as follows [3,36]:

$$Ca^{2+}(aq) + 2HCO_3^-(aq) \leftrightarrow CaCO_3(s) + H_2O(l) + CO_2(g) \quad (2-19)$$

2.5.2 Solubility of Calcium Carbonate

As mentioned earlier the solubility of calcium carbonate in water will change with temperature, pH and partial pressure of CO$_3$. The effects these variables have on the solubility will be discussed with graphs of actual data. Although calcium carbonate does dissolve in water it is considered to be an insoluble salt due to its
relatively low solubility as compared to other salts. For example at 20°C, only 0.0062 grams of CaCO₃ will dissolve in 1 liter of water. Comparatively, at 20°C, 360 grams of NaCl (table salt) will dissolve in 1 liter of water.

2.5.2.1 Effects of Temperature on the Solubility of CaCO₃

Many substances that dissolve in water such as sodium chloride (NaCl, table salt), magnesium sulfate (MgSO₄, epsom salt) and sodium bicarbonate (NaHCO₃, baking soda) will become more soluble in water as temperature increases. As mentioned earlier, calcium carbonate (CaCO₃) has inverse solubility. Thus, localized precipitation will occur as a cold stream that contains high concentrations of calcium carbonate passes a heated plate. The concentration of calcium carbonate in water at 20°C will be about 65 ppm (parts per million) and at 50°C it will decrease to 38 ppm [37]. A more detailed chart of the solubility of calcium carbonate in water can be seen in Figure 2-7.
2.5.2.2 Effects of pH on the Solubility of CaCO₃

As mentioned earlier, the solubility of calcium carbonate changes with the pH of a solution. As pH rises the solubility of calcium carbonate decreases as seen in Figure 2-8[10]. Thus, as pH rises in a system, calcium carbonate will have a tendency to deposit. Figure 2-8 shows the solubility of calcium carbonate in a system as a function of the pH in tap water at 30°C. It often occurs that people will deliberately clean a system by lowering the pH. In fact, as will be seen later in this paper, the system at Lehigh University was periodically cleaned using a pH of 3.0. The pH of the system was lowered using sulfuric acid (H₂SO₄). Although, a low pH will tend to cause corrosion to metal surfaces.
Figure 2-8 Solubility of Calcium Carbonate in Tap Water at 30°C as a Function of pH [10].

2.5.2.3 Effects of Pressure on the Solubility of CaCO₃

As mentioned earlier, the solubility of calcium carbonate will decrease as the partial pressure of carbon dioxide (CO₂) decreases. The partial pressure of CO₂ will drop in correspondence to a drop in atmospheric pressure. Thus, if atmospheric pressure decreases, the solubility of calcium carbonate will decrease. The relationship of the solubility of calcium ions in water at 16°C to the partial pressure of carbon dioxide can be seen in Figure 2-9 [37]. The tip of an impeller blade on a pump is a prime location in a system that can see significant calcium carbonate scale due to pressure drops. Other sudden pressure drops can occur through valves and pipe elbows.
2.5.3 Calcium Carbonate Precipitation Index

For precipitation of calcium carbonate to occur, the solution in which the calcium carbonate is dissolved will have to contain a higher concentration of solute (calcium carbonate) than the equilibrium concentration can handle. At this point, the solution will be super-saturated and precipitation will occur. There are two types of super-saturation, metastable and labile (unstable). These states, along with the stable, undersaturated state can be seen in Figure 2-10. In the stable zone, crystallization in the bulk water will not occur. That is not to say that precipitation will not occur if temperature or pH is raised or pressure is lowered. In the metastable region a spontaneous crystallization is not likely to occur. If by chance, the solution in the metastable is seeded with a crystal of calcium carbonate, it is more likely that

Figure 2-9 Solubility of Calcium ion (Ca\(^{2+}\)) in Water at 16\(^\circ\)C in Contact With CO\(_2\) at Low and High Partial Pressure[37].
spontaneous crystallization will occur. In the labile region, the level of super-saturation is so high that spontaneous crystallization is unavoidable. It has been found that the rate of calcium carbonate scale formation is highly dependent on the levels of super-saturation. In fact, the rate of scale growth increases almost linearly with the degree of super-saturation [38].

![Solubility-Super-Solubility Diagram](image)

**Figure 2-10 Solubility-Super-Solubility Diagram [10]**

Although we know of three states at which a solution can exist, the actual determination of the state in a real system is quite difficult. As can be seen from the previous sections, there are many variables that will determine the state of saturation for calcium carbonate in water. Thus, it is very difficult to determine whether a system is in danger of light or heavy fouling. For this reason many people have developed a few indices which attempt to predict whether a system will have a tendency to form scale. Most of these equations are based on the system’s pH, temperature (T), total dissolved solids (TDS), calcium hardness (CA) and total
The two that we will study are the Langlier Saturation Index (LSI) and the Ryznar Stability Index (SI).

### 2.5.3.1 Langlier Saturation Index

The Langlier Saturation Index was originally created to help in predicting the relative stability of bulk water with regard to calcium carbonate precipitation and scaling. The Langlier Saturation Index is still used for this purpose today. The LSI is based on the saturation pH ($pH_s$) of water. The $pH_s$ is the pH at which water is said to be saturated with calcium carbonate. The calcium carbonate in a saturated condition will neither precipitate or dissolve any more calcium carbonate. The LSI equation is as follows [3]:

$$LSI = pH_{actual} - pH_s$$  \hspace{1cm} (2-20)

where $pH_{actual}$ is the experimentally measured pH of the bulk water or solution and $pH_s$ is as follows:

$$pH_s = 12.3 - (\log_{10}(Ca) + \log_{10}(TA) + 0.025(T) - 0.011(TDS)^{1/2})$$  \hspace{1cm} (2-12)

where:

- $Ca$ = Calcium hardness as ppm CaCO$_3$
- $TA$ = Total alkalinity as ppm CaCO$_3$
- $T$ = Temperature as °C
- TDS = Total dissolved solids ppm
Water with a positive LSI can be expected to scale and water with a negative LSI will be expected to corrode. Typically, systems will be operating with an LSI in the range of $-3.0$ (heavy corrosion) to $+3.0$ (heavy scaling). LSI is usually used for cooling systems when considering chemical treatment proposals and water management. However, the use of LSI can sometimes be used beyond its original intentions for the following reasons. LSI provides insight into the potential of CaCO$_3$ scaling, but not for other scaling and fouling risks. Also, accurate calculation of LSI requires correct experimentally determined pH$_{\text{actual}}$, which can sometimes vary through a large industrial water system. Lastly, LSI was never intended for fast flowing systems as is seen in most water cooling systems [3]. Despite its limitations, the Langlier Saturation Index provides a quick and easy initial assessment of the scaling probability of a water system.

2.5.3.2 Ryznar Stability Index

As a result of some of the limitations of the Langlier Saturation Index, the Ryznar Stability Index was created (SI). The SI is a direct derivation of the LSI and is based on observed field data. It is generally considered more useful for systems that have flow rates over .6 m/sec as would occur in a cooling system. The equation for SI is as follows:

\[
SI = 2pH_s - pH_{\text{actual}} \tag{2-13}
\]

where pH$_{\text{actual}}$ is once again an experimentally measured value of the bulk water or solution. The value for pH$_s$ can be calculated using the same equation 2-12 as is used
in calculating the LSI. Typically the range for SI will vary between 3.5 and 9.0, where 3.5 will create heavy scaling and 9.0 will create heavy corrosion [3].

2.5.4 Types of Calcium Carbonate Scale

Calcium carbonate is capable of crystallizing in three polymorphic forms: calcite, aragonite and vaterite [39]. The conditions under which each of the types of CaCO₃ forms will vary depending on environmental conditions.

2.5.4.1 Physical Characteristics of Calcite

Calcite is thermodynamically the most stable variety at ambient temperature [40]. Calcite usually forms a crystalline hexagonal shape as can be seen in Figure 2-11 (a). Calcite can also have a cubic crystalline structure as seen in Figure 2-11 (b). The calcite crystal is generally formed when surrounding conditions are at temperatures below 30°C. Calcite can be easily removed from surfaces with a weak acid such as vinegar. Calcite is also less adherent to surfaces than aragonite [41,10].

![Figure 2-11](a) SEM Image of Hexagonal Calcite Crystalline Structure at 200 μm Magnification. (b) SEM Image of Cubic Calcite Crystalline Structure
in calculating the LSI. Typically the range for SI will vary between 3.5 and 9.0, where 3.5 will create heavy scaling and 9.0 will create heavy corrosion [3].

2.5.4 Types of Calcium Carbonate Scale

Calcium carbonate is capable of crystallizing in three polymorphic forms: calcite, aragonite and vaterite [39]. The conditions under which each of the types of CaCO₃ forms will vary depending on environmental conditions.

2.5.4.1 Physical Characteristics of Calcite

Calcite is thermodynamically the most stable variety at ambient temperature [40]. Calcite usually forms a crystalline hexagonal shape as can be seen in Figure 2-11 (a). Calcite can also have a cubic crystalline structure as seen in Figure 2-11 (b). The calcite crystal is generally formed when surrounding conditions are at temperatures below 30°C. Calcite can be easily removed from surfaces with a weak acid such as vinegar. Calcite is also less adherent to surfaces than aragonite [41,10].

Figure 2-11 (a) SEM Image of Hexagonal Calcite Crystalline Structure at 200 μm Magnification. (b) SEM Image of Cubic Calcite Crystalline Structure
2.5.4.2 Physical Characteristics of Aragonite

Aragonite is another form of calcium carbonate. The crystal structure of aragonite will typically form when the surrounding environmental conditions are at 60°C or above. The crystal structure of aragonite generally looks like needles and is very porous as seen in Figure 2-12. The technical name for the crystal structure is orthorhombic. Unlike calcite, aragonite is usually difficult to remove and is more dangerous to heat transfer equipment for this reason [41,10].

![SEM Image of Aragonite Crystalline Structure at 10 μm Magnification](image)

2.5.4.3 Physical Characteristics of Vaterite

Vaterite is the third type of crystalline structure of which calcium carbonate can assume. Vaterite is the least stable of all the calcium carbonate crystalline structures and will usually transform into either calcite or aragonite in a later stage of...
2.5.4.2 Physical Characteristics of Aragonite

Aragonite is another form of calcium carbonate. The crystal structure of aragonite will typically form when the surrounding environmental conditions are at 60°C or above. The crystal structure of aragonite generally looks like needles and is very porous as seen in Figure 2-12. The technical name for the crystal structure is orthorhombic. Unlike calcite, aragonite is usually difficult to remove and is more dangerous to heat transfer equipment for this reason [41,10].

![SEM Image of Aragonite Crystalline Structure at 10 μm Magnification](image)

Figure 2-12 SEM Image of Aragonite Crystalline Structure at 10 μm Magnification

2.5.4.3 Physical Characteristics of Vaterite

Vaterite is the third type of crystalline structure of which calcium carbonate can assume. Vaterite is the least stable of all the calcium carbonate crystalline structures and will usually transform into either calcite or aragonite in a later stage of
growth. Vaterite generally has a spherical crystalline shape as seen in Figure 2-13, but can also assume hemispherical, flower or lens shapes [39,42].
growth. Vaterite generally has a spherical crystalline shape as seen in Figure 2-13, but can also assume hemispherical, flower or lens shapes [39,42].

Figure 2-13 SEM Image of Vaterite Crystalline Structure
As was mentioned in the introduction, calcium carbonate scaling is a widely known problem in industrial systems that utilize make-up water from ground sources. The yearly loss associated with the problem has been discussed in the introduction. In addition, the loss in thermal and pressure efficiencies has been established in Chapter 2. It is evident at this point that efforts in reducing and preventing calcium carbonate scale formation would be beneficial. Many methods for preventing and reducing calcium carbonate scale are in fact in use today. Traditionally, chemicals are added to systems to help prevent the formation of scale. Chemical treatment has been proven to work in industrial systems in preventing and removing scale. Unfortunately one dosage of chemical treatment is not permanent and in order for it to work chemicals need to be added on a regular basis. In addition, many of these chemicals are hazardous to the environment.

In recent history many other methods of calcium carbonate scale prevention have been developed to replace chemical treatment. These methods can be classified as non-traditional methods. These methods include; ion exchange, reverse osmosis, ozonation, vortex treatment, permanent magnets, AC magnetic treatment, radio frequency treatment and finally electrostatic water treatment. The effectiveness of some of these non-traditional treatments is still uncertain and their applications to industrial systems are questionable. This section will help to clarify some of the
mechanistic theories that exist for these non-traditional types of treatments. In some cases the effectiveness of these treatments will be clarified with studies that have been done on them. Unfortunately, in certain cases, some of the studies of effectiveness completed on the same type of treatment will conflict. Due to the nature of this thesis, more attention will be given to studies that have been completed on electrostatic water treatment.

3.1 Natural Inhibitors to Calcium Carbonate Scale Formation

Naturally occurring calcium carbonate scale formation inhibitors will exist in a system without the addition of chemicals. These types of inhibitors such as copper(II) and iron(II) ions have been shown in laboratory experiments to reduce the rate of which calcium carbonate will scale. Iron(II) has also been shown to reduce calcite growth in industrial systems. Copper(II) and iron(II) ions will exist with varying degrees of concentration in an industrial system if copper and iron piping is present. The effectiveness on an industrial system is unknown but the mechanism of these natural inhibitors as learned through experimentation will be discussed in this section.

3.1.1 Calcite Growth Inhibition by Copper(II)

The effectiveness of the inhibition of calcite growth by copper(II), also known as Cu(II) ions, depends not only on copper concentration but also on calcite supersaturation [43,44]. In the experiments conducted by Katz and Parsieglia, an almost immediate decrease in calcite deposition was noticed as soon as copper(II)
ions were added to a solution. It was believed that the copper ions were fitting into the crystal lattice of the calcite and preventing the formation of scale growth. Essentially, the copper(II) ions were competing with the calcium carbonate for places to deposit. As more copper(II) ions were deposited in the crystal lattice the concentration of copper(II) ions was decreased in the solution. It was noticed as the concentration of copper(II) ions was decreased there was a systematic increase in calcium carbonate deposition. It has also been found that the effectiveness of the copper(II) ions will increase with increasing supersaturation. That is, the more calcium carbonate that is added to a system the more effective the copper(II) is on inhibiting deposition [43,44]. Copper(II) would be found in industrial water systems if copper piping was present.

3.1.2 Calcite Growth Inhibition by Iron(II)

Many investigators have also noticed a reduction in scaling in industrial systems and piping when iron(II), also know as Fe(II), was added. Laboratory experiments have also been conducted on the effectiveness of iron(II) on the inhibition of calcite growth. Experimentally, it has been found that, with increasing concentrations of Fe(II) the degree of calcite growth inhibition increases[45]. At Fe(II) concentrations of $10^{-4}$M and higher, the inhibiting effect is so strong that essentially no calcium is removed from solution initially. In industrial systems Peters and Stevens reported a 26% decrease in deposition of CaCO$_3$ on the walls of a crystallizer when .6 ppm of Fe(II) were added [46]. Hasson and Bramson reported a
40% reduction in scaling rate of a test pipe when 1.4 ppm of FeSO₄ were added to the water [47]. Iron(II) can be found in water systems that utilize mild steel for piping.

3.2 Traditional Chemical Treatment

Over the years the development of chemical water treatment has changed quite a bit. In the early 1930's and 40's most water treatment was based on the addition of silicates, starches, lignins, chromates, sulfuric acid and chlorine. In the 1950's and 60's the additions of zinc and polyacrylates were introduced. In the late 1960's and 70's the introduction of organic phosphates and organic polymers such as polymaleic acid commenced [3].

Some of these chemicals have proven to work quite effectively but in some cases they are very detrimental to the environment. Sulfuric acid has been proven to be an excellent scale growth inhibitor and remover. The use of sulfuric acid, however, requires careful analytical control of water systems. Furthermore, adding too much sulfuric acid will corrode mild steal. Lastly, sulfuric acid is detrimental to the environment.

As mentioned, sulfuric acid is a chemical that was introduced to the water treatment industry in the 30's and 40's. Today, organic phosphates and organic polymers are slowly replacing sulfuric acid. These chemicals have proven to act as hardness stabilizers and scale growth retardants. It has been found that an addition of 1 to 10 ppm concentrations of the organic phosphates will in effect be absorbed in the crystalline structure of calcium carbonate as it precipitates. This distorts the crystalline structure and prevents a small crystal from agglomerating into a larger
crystal. As a result, scale formation is reduced. Some of the copolymers produced in
the 1980's have also proven to be excellent dispersants. As a generality, most cooling
water foulants tend to have a slightly negative charge, and consequently these
polymers with dispersing functions tend to be negatively charged. This in effect will
increase the repelling forces between particles and as a result, particles will not
agglomerate. These chemicals have also proven to act as corrosion inhibitors and
metal surface cleaners. Organic phosphates and organic polymers have proven to be
the most effective in water treatment but on a tonnage basis, sulfuric acid, zinc, and
chlorine are still used more due to their low cost.

3.3 Non-Traditional Chemical and Non-Chemical Water Treatment

The use of “non-traditional” water treatments can range from industrial
systems to domestic environments. These treatments will include ion exchange and
ozonation, which are classified as “non-traditional” chemical treatments. We will
also study reverse osmosis and vortex treatment, which are classified as “non-
traditional non-chemical” water treatments. The effectiveness of these treatments as
they apply to industrial and domestic settings will be studied.

3.3.1 Ion Exchange Water Treatment

Ion exchange is a unit process by which ions of a given species are displaced
from an insoluble exchange material by ions of a different species in solution [48].
Typically, this type of water treatment is seen in domestic water softening devices,
where sodium ions from a cationic exchange resin replace the calcium and
magnesium ions in the treated water. This in effect reduces the hardness of the water and its ability to form calcium carbonate scale.

3.3.2 Ozonation Water Treatment

The use of ozone in cooling tower water treatment has received more attention in recent years. Ozone is the fourth most powerful oxidizing agent, and the most powerful oxidizing agent available to industrial water treatment. Since ozone is such a powerful oxidization reaction agent, its use for controlling calcium carbonate scale has been proposed. It has been reported by Wu and Chan [49], that ozonation will weaken the bonding between calcium carbonate and the heat transfer surface and will cause cracks in existing fouling layers. They also reported that ozone could decrease the initial fouling rate due to the self-decomposition of ozone into oxygen on the heated surface that formed bubble patches to retard the initial fouling process. There are many other reports that show ozone can efficiently prevent scale formation [50,51]. There are also many reports that show ozone is not an effective method for water treatment [52,53].

3.3.3 Reverse Osmosis Water Treatment

Reverse osmosis (RO) also called hyperfiltration is the finest filtration known. Water treated using RO is separated from dissolved salts in solution by filtering through a semi permeable membrane at a pressure greater than the osmotic pressure caused by the dissolved salts in the untreated water. Reverse osmosis is unique in the sense that it can filter soluble ions, which with a standard filter is impossible.
Generally, reverse osmosis is used for obtaining ultra pure water on a smaller scale for drinking or pharmaceuticals and is not used for cooling treatment plants. The volumes of water treated are usually very low and the process is generally expensive.

3.3.4 Vortex Technology Water Treatment

Vortex water treatment manufactured by Chesterton® is a technology that has recently appeared. Vortex technology operates by colliding two water jet streams at high velocities. Some commercially available high-pressure jet fluidizers are capable of pressure drops of 2 kbar and jet velocities approaching 200 m/s [54]. The kinetic energy of the collision creates cavitations, which in turn creates a local rise in temperature and in theory should precipitate calcium carbonate. The precipitated calcium carbonate can then be filtered off and kept out of the bulk water. This technology has been studied by Suslick [54] in lab conditions and seems to work with $I_3^-$ precipitation.

3.4 Non-Chemical Magnetic and Electromagnetic Water Treatment

Non-chemical magnetic and electromagnetic water treatments have been developed in another effort to replace chemicals with a clean and cheap solution to calcium carbonate scale formation. Magnetic treatment exposes water to a permanent magnetic field and has been incorporated into industrial and domestic applications. Electromagnetic water treatment utilizes varying electric fields and varying magnetic fields to reduce calcium carbonate scale deposition. Electromagnetic water treatment has also been labeled as electronic anti-fouling technology (EAF) and pulsed power
technology (PPT). Research has also been completed on the effects of radio frequency on calcium carbonate particles. All of these technologies will be clearly explained and reviewed in this chapter. Once again, the conclusions on the effectiveness of some of these technologies vary from experiment to experiment.

3.4.1 Magnetic Water Treatment

Magnetic water treatment consists of passing water through a strong (1,000 to 10,000 Gauss) magnetic field. The magnetic field can be generated by permanent magnets or electromagnets that will emit a constant magnetic field. The magnets are usually installed in or on a feed water pipe in industrial systems. A number of theories on the mechanism to explain how magnetic treatment works have been theorized. One is that the magnetic field alters the properties of water. This theory has been thoroughly examined and no experimental or theoretical work has been able to sustain it [55,56,45]. Another theory is that the magnetic field will directly affect the precipitation of scale forming salts [57]. The most probable theory is that the magnetic field will attract ferrous materials such as Fe(II) that will inhibit the growth of calcium carbonate particles. These particles are then carried down stream to boilers where they will further inhibit calcium carbonate growth [55,56]. The effectiveness of magnetic water treatment is littered with controversy. Many researchers have claimed to see an effect on calcium carbonate particles and deposition [58,59,60,61]. Whereas other researchers have found that magnetic treatment has no effect on calcium carbonate deposit [55,62,63,64].
3.4.2 Electromagnetic Water Treatment

Electromagnetic water treatment also known as electronic anti-fouling treatment (EAF) or pulsed power treatment (PPT), is another form of non-chemical non-traditional water treatment. Fortunately, this particular type of treatment has had a greater quantity of research completed on its effectiveness. The operation of electromagnetic water treatment is involved. A diagram of a typical treatment device used in experimentation at Drexel University can be seen in Figure 3-1 [10].

Typically, a 14 gauge single stranded wire is wrapped around a feed pipe to a heat exchanger. The two ends of the wire are connected to the ED2000 unit, which produces a pulsing square wave current to create a time-varying magnetic field inside the pipe. Subsequently, the time varying magnetic field creates an induced electric field inside the pipe, which also oscillates with time.

Figure 3-1 Schematic Diagram of the Operation of an electronic ant-fouling unit. Provided by Drexel University [10]
There are many companies that manufacture electromagnetic water treatment devices. Some of these companies include Sonical, Scalewatcher®, PLR Parrot® and Clearwater Systems LLC. All of these companies have reported positive results on their product and some have even backed their claims with field data. Researchers at Drexel University and the University of Connecticut have also conducted studies on the effectiveness of electromagnetic water treatment and have seen positive results. There is a conflict however between the findings at the two Universities when it comes to the effects of electromagnetic water treatment on calcium carbonate particle formation. The Drexel University group believes that the treatment will induce calcium carbonate particles to form with no particular orientation or crystal structure. Whereas, the University of Connecticut group believes that aragonite is formed in the same conditions. The two research teams also disagree on the adhesion characteristics of calcite and aragonite.

3.4.2.1 Studies Conducted at Drexel University

Choi [10] has proposed that for an induced electric field in the clockwise direction, positive ions move in the clockwise direction while negative ions move in the counterclockwise direction. This results in the collision of particles and the precipitation of calcium carbonate in the bulk solution. When the induced field is changed to the counterclockwise direction, the positive ions will now move in the counterclockwise direction and the negative ions will move in the clockwise direction, once again resulting in particle collision and precipitation. The precipitated particles will provide nucleation sites for additional calcium carbonate and hence will
compete with heat exchanger surfaces. This competition for calcium carbonate between the precipitated particles and the heat transfer surface is the mechanism that reduces scale on the heat transfer surface. In addition, Choi has found that the electromagnetic treatment will produce calcium carbonate crystals of small elliptic shapes between 3-10 μm with no particular orientation, which proved to be easy to remove from a heat transfer surface. Whereas, without treatment, a tougher more dense Aragonite was formed with crystal sizes ranging between 2-25 μm and proved to be difficult to remove from heat transfer surfaces.

3.4.2.2 Studies Completed at the University of Connecticut

The University of Connecticut also found that electromagnetic water treatment could inhibit calcium carbonate scale growth. Dresty [65] stated that electromagnetic water treatment lowers the activation energy required to nucleate calcium carbonate. The lower activation energy will produce a beneficial aragonite, as opposed to a less desirable calcite. Dresty has stated that the aragonite produced can be removed from a system during a normal blow down process, unlike the tenacious calcite that would form without treatment. The University of Connecticut also found that in some of the field studies, calcium carbonate scale was prevented from forming and was even removed from metal surfaces.

3.4.3 Effects of Radiofrequency on Calcium Carbonate

Radiofrequency is an electromagnetic radiation that is characterized by frequencies between 300 MHz and 3 kHz. The effect of radiofrequency electric fields
on the zeta potential of calcium carbonate has been studied under laboratory conditions [66,67,68,69,70]. In particular, Chibowski and Holysz [70] prepared a calcium carbonate suspension in doubly distilled water or .01 M NaCl solution at several pH values. To expose the suspension to the radiofrequency field, about 60 ml of each suspension were placed in a glass tube sealed at both ends with rubber corks into which platinum electrodes were fixed. The distance between the electrodes was 20 cm. The applied radiofrequency field was 44 MHz and 60 Volts peak to peak. The time of exposure ranged from 5 to 30 minutes. The zeta potential was measured 2-3 minutes after exposure with a Ekobudex Zetameter. Chibowski and Holysz found that the negative zeta potential of CaCO₃ changed in an oscillatory fashion depending on the time of exposure to the radiofrequency field. The observed changes in zeta potential are believed to be a result from the changes in the surface charge of calcium carbonate and the structure of the water film at the surface [70].

3.5 Electrostatic Water Treatment

Electrostatic water treatment is a process by which an electric field is distributed through water. It has been proposed that this distributed electric field will affect the deposition of calcium carbonate. Figure 3-2 shows the operation of an electrostatic water treatment device in a pipe bend and Figure 3-3 shows the operation of an electrostatic water treatment device in a side stream reaction chamber.
The electrostatic water treatment device described in the following paragraphs is that which was used to run experiments at Lehigh University. Although the operating principles for electrostatic water treatment devices are consistent between manufacturers, some of the dimensions and materials may differ.
An electrostatic water treatment device consists of a voltage supply, an electrostatic rod and a reaction chamber. The voltage supply delivers on the order of 25,000 volts DC and up to maximum of .2 mA of current. The electrostatic rod consists of an electrode made of a conducting material with a radius of 0.0175 meters. The electrode is coated with a dielectric insulating material as seen in Figure 3-4, with an inner radius of 0.0175 meters and an outer radius of 0.0215 meters. The electrically grounded reaction chamber is made of stainless steel and has a radius of 0.0556 meters. The reaction chamber used at Lehigh University is of the side stream style. A schematic of the electrostatic water treatment device used at Lehigh University can be seen in Figure 3-5.

**Figure 3-4 Construction of Electrostatic Rod**
As seen, the electrostatic rod is placed inside of the reaction chamber and water is allowed to flow in the reaction chamber and around the electrostatic rod. When the voltage is supplied to the electrostatic rod an electric field is generated through the flowing water between the electrostatic rod and the electrically grounded reaction chamber. The magnitude and calculations of the electric field will be fully described in the following chapter, Chapter 4.

As mentioned earlier, most cooling water foulants tend to have a slightly negative charge. Typically, chemicals such as copolymers can be added to water to act as dispersants. Since the copolymers have a negative charge they effectively increase the repulsion between calcium carbonate particles and as a result prevent
particles from agglomerating. Agglomeration in industrial water systems is usually detrimental for the reason that as particles in the momentum region become larger, the rate of deposition increases, as seen in Figure 2-2.

Electrostatic water treatment has been proposed to operate as a dispersant to foulants, particularly calcium carbonate particles. It has been theorized that the electric field passing through the water will in effect induce a like surface charge on foulants and calcium carbonate particles. The similar charge on particles will prevent agglomeration and as a result deposition will be decreased. Unfortunately, very little research has been completed on electrostatic water treatment. In addition, very little to no research has been conducted on the effects of electric fields on particle size and surface charge. Therefore, it is very difficult to make conclusions on the mechanism by which Electrostatic Water Treatment would operate. The research completed at Lehigh University has attempted to determine whether electrostatic water treatment will affect calcium carbonate particle size, surface charge and agglomeration. In addition, a direct experiment on the effectiveness of electrostatic water treatment on calcium carbonate scale formation has been completed. As an additional experiment, the effect of electrostatic water treatment on bacterial growth has been completed. The combination of these three experiments will give the reader a better understanding of the effectiveness of electrostatic water treatment.

3.5.1 Manufacturers of Electrostatic Water Treatment Systems

There are many manufacturers that currently produce and sell electrostatic water treatment devices to industries that use large amounts of make up and
recirculating water. Most commonly, electrostatic water treatment devices are used in HVAC systems. Some of the companies that manufacture electrostatic water treatment devices are Chemfree Water Systems, Inc., Ion Stick®, Zeta Rod™, Avoca-tec, Inc. and Permaclean™.

3.5.2 Research Completed on Electrostatic Water Treatment and the Effect of Electrostatics on CaCO₃ Particles

As mentioned earlier, very little research has been completed on electrostatic water treatment. After a complete literature review, it was found that most research has been completed by companies that have purchased electrostatic water treatment devices or by companies that distribute water treatment chemicals. Most research on electrostatic water treatment has been completed in the field on existing water usage systems. Conclusions on the effectiveness of electrostatic water treatment by these companies are inconsistent. Some of the conclusions report that electrostatic water treatment has had no effect on fouling, while others claim that fouling and bacterial growths are reduced. In the following sections we will review some of the studies completed on electrostatic water treatment. From the literature collected, it is very difficult to make conclusions on the effectiveness of electrostatic water treatment. For this reason, further research in this field needs to be completed in a controlled experimental setting where quantitative and qualitative data is collected and analyzed.
3.5.2.1 Experiment Completed by ProChemTech

ProChemTech is a chemical supplier that has compiled numerous case history reports on various types of water treatments. One of the case history reports on electrostatic water treatment reviewed the Zeta Rod™ developed by the Zeta Corporation [71]. In 1994 a Zeta Rod™ was installed in a cooling tower at the Fort McDowell Casino in Fort McDowell, AZ. After the installation, a substantial buildup of precipitated material was found at the base of the cooling tower. The precipitates were a result of the rise in pH and alkalinities, which was caused by the rise in cycles of the water. The cooling tower experienced severe scaling and was later cleaned with acid. The heat exchangers in the system also experienced heavy fouling and needed continuous cleaning after the first year of Zeta Rod™ operation. ProChemTech concluded that the Zeta Rod™ cannot control calcium based formation in a standard cooling tower with scaling makeup water.

3.5.2.2 Experiment Completed by Queensland University of Technology on Permaclean Water Treatment System

Dr. Ian Moore of Queensland University prepared an interim report on Permaclean water treatment systems that were installed in three separate locations [72]. The Permaclean water treatment systems were installed in cooling systems and data was collected qualitatively over a six to seven week period. It was found that at all three sites there was no evidence of biofilm growth on the interior surfaces of the cooling towers. There were also signs of elimination and/or softening of scale of
varying degrees at each site. Lastly, it was found that microbial levels were maintained at levels below the AS3666 guidelines. The data collected by Dr. Ian Moore would suggest that electrostatic water treatment has an effect on biofilm, scale formation and bacterial growth.

3.5.2.3 Tests on Non-chemical Scale Control Devices

G. J. C Limpert and J. L. Raber also completed research on electrostatic water treatment [73]. Their research was conducted on a two-tube shell and tube heat exchanger with steam applied to the shell side to provide heat. The data collected was measured quantitatively by weighing the scale that formed on the heat exchanger surface. The weight of scale deposited during electrostatic water treatment was then compared to the weight of scale deposited without treatment. Multiple experiments were completed using four different electrostatic water treatment devices, labeled ES-I, ES-II, ES-III, and ES-IV. Each of the four devices were supplied with between 5,000 and 10,000 volts and less than 10 watts. It was concluded that the electrostatic devices did not significantly reduce the amount of calcium carbonate scale formed.

3.5.2.4 An Analytical Review of Water Conditioning Devices

J. Fred Wilkes and Ray Baum provide a non-experimental explanation of the reasons for which electrostatic water treatment should not work [74]. They found that most electrostatic treatment literature claims that water exposed briefly to the electrostatic force field will exhibit residual scale-prevention and scale-removal effects in water-using equipment far downstream. They noted that these claims of
residual scale prevention and removal are questioned since electrostatic effects, if confirmed, should apply only during the few seconds of passage through the electric field. In addition, since no current flows other than dielectric leakages, little or no work is done on the scale forming material. Wilkes and Baum also studied three case histories of electrostatic water treatment as applied to industrial systems. They found that in all cases the electrostatic water treatment device did not work and within a year they were removed and replaced with chemical treatments.

3.5.2.5 Studies on the Effects of CaCO₃ Particles in an Electric Field

Studies have also been completed on the effects of electrostatic fields on CaCO₃ particles. This study of electric fields on particles in suspension is often denoted as electrophoresis. Yukawa, Kobayashi, Yoshida and Iwata studied the effects of calcium carbonate particles suspended in water that was placed between two electrodes with electric fields between 0 and 9 volts/cm [75]. It was found that the settling rate of CaCO₃ particles would increase with increasing electric field. These studies will give us some insight into the effects of electrostatic water treatment on calcium carbonate particles as they pass through the reaction chamber. This study does not give us any insight into the long-term effects, if any, of electric fields on calcium carbonate particles after they have passed out of the electric field.
CHAPTER 4: Investigation of the Electric Fields Associated With Electrostatic Water Treatment Technology

A typical electrostatic water treatment device generates an electric field in flowing water using a cylindrically shaped electrode which is coated with a dielectric material. In order to understand the mechanism by which electrostatic water treatment has been proposed to work one must first understand the principles of Gauss's law and the characteristics of electric fields in Cartesian and cylindrical coordinates. In Section 4.1, the basic laws of electrostatics will be discussed. In Section 4.2 we will introduce some equations which describe the electric fields starting with the most simple geometry and then completing the section with the more complex geometries which electrostatic water treatment entails. Section 4.3 will describe lossy media and its connection to electrostatic water treatment. Lastly, in Section 4.4 we will compare the strengths of electric fields generated for each geometry.

4.1 General Electrostatic Field Equations

An electrostatic field is emitted when an object contains a net positive or net negative charge. The electrostatic field or electric field is generated when current does not flow, whereas an electromagnetic field is generated when current does flow. Electric field \( E \) can be simply described as voltage \( V \) per unit length \( L \). More
precisely, the electric field can be determined from the gradient of a scalar function $V$ called the potential, having units of volts [kg-m$^2$-s$^{-3}$-A$^{-1}$].

$$E = -\nabla V$$  \hspace{1cm} (4-1)

The minus sign is used by convention so that the electric field will point in the direction of decreasing strength or potential.

It follows that if a volume distribution of charge $\rho$ is completely surrounded by a closed Gaussian surface $S$, Gauss's Law is:

$$\oint_S \varepsilon_0 E \cdot ds = \int_\nu \rho dV$$  \hspace{1cm} (4-2)

where $\varepsilon_0$ is the permittivity of free space and has a value of:

$$\varepsilon_0 = \left(4\pi \times 10^{-7} \text{ c}^2\right)^{-1}$$  \hspace{1cm} (4-3)

Next, the left hand side can be changed to a volume integral using the divergence theorem, where:

$$\oint_S \varepsilon_0 E \cdot ds = \int_\nu \nabla \cdot (\varepsilon_0 E) dV = \int_\nu \rho dV$$  \hspace{1cm} (4-4)

This then yields the point form of Gauss's law:

$$\nabla \cdot (\varepsilon_0 E) = \rho$$  \hspace{1cm} (4-5)

where $\rho$ is the volume charge density (coul/m$^3$). In cases of a grounded conducting material or an uncharged capacitor at time 0, there is no volume charge and Gauss's law requires:
\[ \nabla \cdot (\varepsilon_0 \mathbf{E}) = 0 \]  
\hspace{1cm} (4-6)

It must also follow that the line integral of \( \mathbf{E} \) between the electrodes must be the applied voltage \( V \):

\[ \int_0^L E_x \, dx = V \]  
\hspace{1cm} (4-7)

In addition to the electric field equations it is important to understand the governing equations for capacitance and resistance. A capacitor is a device that can store a charge. The magnitude of this charge is described as capacitance and has units of farads. Capacitance \( C \) is defined as the magnitude of the ratio of total free charge on either electrode to the voltage difference between electrodes. The equations for capacitance are as follows:

\[ C = \frac{q_f}{V} \]  
\hspace{1cm} (4-8)

\[ C = \frac{\varepsilon A}{L} \]  
\hspace{1cm} (4-9)

Equation 4-8 is the ratio of total free charge \( q_f \) in a capacitor to the voltage \( V \) difference between the capacitor electrodes. Equation 4-9 also describes capacitance as the ratio of capacitor material permittivity \( \varepsilon \) and the cross sectional area \( A \) to the gap length \( L \) of the electrodes. Permittivity is the product of relative permittivity \( \varepsilon_r \), or dielectric constant) and the permittivity of free space \( \varepsilon_0 \):
Typically we use the relative permittivity also called the dielectric constant. As seen from Equation 3-9 the capacitance of a system can be simply increased by placing an object of higher dielectric constant in between the electrodes. Some commonly used relative permittivity values can be seen in Table 4-1.

Table 4-1 The relative permittivity for various common substances at room temperature [76].

<table>
<thead>
<tr>
<th>Substance</th>
<th>$\varepsilon_r = \varepsilon / \varepsilon_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Tetrachloride</td>
<td>2.2</td>
</tr>
<tr>
<td>Ethanol</td>
<td>24</td>
</tr>
<tr>
<td>Kynar</td>
<td>7</td>
</tr>
<tr>
<td>Methanol</td>
<td>33</td>
</tr>
<tr>
<td>n-Hexane</td>
<td>1.9</td>
</tr>
<tr>
<td>Nitrobenzene</td>
<td>35</td>
</tr>
<tr>
<td>Pure Water</td>
<td>80</td>
</tr>
<tr>
<td>Barium Titane</td>
<td>2100</td>
</tr>
<tr>
<td>Borosilicate Glass</td>
<td>4</td>
</tr>
<tr>
<td>Ruby Mica</td>
<td>5.4</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>2.2</td>
</tr>
<tr>
<td>Polyvinyl Chloride</td>
<td>6.1</td>
</tr>
<tr>
<td>Teflon</td>
<td>2.1</td>
</tr>
<tr>
<td>Plexiglas</td>
<td>3.4</td>
</tr>
<tr>
<td>Paraffin Wax</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Next we can discuss resistance. Resistance (R) is measured in unit of ohms (\(\Omega\)) and is described by the following equation:

$$R = \frac{L}{\sigma A} \quad (3-11)$$
Where \( L \) is length, \( A \) is cross sectional area and \( \sigma \) is conductivity (siemen/m), where siemen = 1/ohm. The reciprocal of conductivity is simply resistivity (\( \rho \)) measured as ohm-meters. Some common conductivity measures are listed in Table 4-2.

### Table 4-2 The conductivity for various common substances at room temperature [76]

<table>
<thead>
<tr>
<th>Substance</th>
<th>( \sigma [\text{siemen/m}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver</td>
<td>( 6.3 \times 10^7 )</td>
</tr>
<tr>
<td>Copper</td>
<td>( 5.9 \times 10^7 )</td>
</tr>
<tr>
<td>Gold</td>
<td>( 4.2 \times 10^7 )</td>
</tr>
<tr>
<td>Lead</td>
<td>( .5 \times 10^7 )</td>
</tr>
<tr>
<td>Tin</td>
<td>( .9 \times 10^7 )</td>
</tr>
<tr>
<td>Zinc</td>
<td>( 1.7 \times 10^7 )</td>
</tr>
<tr>
<td>Carbon</td>
<td>( 7.3 \times 10^{-4} )</td>
</tr>
<tr>
<td>Mercury</td>
<td>( 1.06 \times 10^6 )</td>
</tr>
<tr>
<td>Pure Water</td>
<td>( 4 \times 10^{-6} )</td>
</tr>
<tr>
<td>Cooling Water</td>
<td>( 0.21 )</td>
</tr>
<tr>
<td>Nitrobenzene</td>
<td>( 5 \times 10^{-7} )</td>
</tr>
<tr>
<td>Methanol</td>
<td>( 4 \times 10^{-5} )</td>
</tr>
<tr>
<td>Ethanol</td>
<td>( 1.7 \times 10^{-7} )</td>
</tr>
<tr>
<td>Hexane</td>
<td>( 1.7 \times 10^{-18} )</td>
</tr>
<tr>
<td>Kynar</td>
<td>( 5 \times 10^{-13} )</td>
</tr>
</tbody>
</table>

These equations will give us a basis for solving the electric field for any given shape. We will be mainly concerned with the electric fields generated by cylindrical shapes. Before we delve in to the cylindrical shapes we should first understand the
basics and study the electric field for a two dimensional Cartesian coordinate problem.

4.2 Applied Electrostatic Field Equations

Now that we have an understanding of some of the base equations for electric fields we now need to apply them. We will start out with a simple model to get an understanding on the manipulations of the equations and then we will apply the equations to a more complex cylindrical geometry.

4.2.1 Electric Field for Parallel Plate Resistors and Capacitors

First we will introduce a parallel plate resistor as seen in Figure 4-1. As seen, the red material is resistive/capacitive and the gray thin sections are the positive and negative conductive electrodes separated by a distance (L). The electric field in the resistor/capacitor is relatively easy to calculate due to its perpendicular geometry with respect to the electrodes.

![Parallel Plate Geometry](image)

**Figure 4-1** Parallel Plate Geometry
Using Gauss’s law with no volume charge, because the resistor is conductive, denotes that the electric field is constant:

\[ \nabla \cdot (\varepsilon \mathbf{E}) = 0 \Rightarrow \frac{dE_x}{dx} = 0 \Rightarrow E_x = E_0 \quad (4-12) \]

The line integral of \( E_x \) between the electrodes must be the applied voltage \( V \):

\[ \int_0^L E_x \, dx = V \Rightarrow E_0 = V / L \quad (4-13) \]

so the electric field for a parallel plate resistor can be defined as:

\[ E_0 = V / L \quad (4-14) \]

Equation 4-14 describes the electric field for a parallel plate resistor and capacitor. This is intuitive, since the electric field in a simple system is only governed by voltage and length and independent of the material filling the space in between the plates. Table 4-3 shows the electric fields for five differing input voltages, 30,000, 25,000, 20,000, 10,000, 5,000, with a constant material thickness of \( L = .004 \) meters.

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>Material Thickness (m)</th>
<th>Electric Field (V/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30,000</td>
<td>0.004</td>
<td>7,500,000</td>
</tr>
<tr>
<td>25,000</td>
<td>0.004</td>
<td>6,250,000</td>
</tr>
<tr>
<td>20,000</td>
<td>0.004</td>
<td>5,000,000</td>
</tr>
<tr>
<td>10,000</td>
<td>0.004</td>
<td>2,500,000</td>
</tr>
<tr>
<td>5,000</td>
<td>0.004</td>
<td>1,250,000</td>
</tr>
</tbody>
</table>
4.2.2 Electric Field for Cylindrical Geometries

Now we introduce and analyze the electric field for a cylindrical geometry as seen in Figure 4-2. Voltage is supplied in the conductive gray area. An electric field is then created in the resistive/capacitive red area from (a) to (b).

![Figure 4-2 Cylindrical Electrode Geometry](image)

As seen in Figure 4-2 the cylindrical geometry has a center electrode of radius a, and a resistor/capacitor of radius b. To determine the electric field distributed through the resistor/capacitor we again start with Gauss’s equation but instead of Cartesian coordinates we use polar coordinates. In polar coordinates Gauss’s equation becomes:

\[ \nabla \cdot (\varepsilon \mathbf{E}) = 0 \Rightarrow \frac{1}{r} \frac{\partial}{\partial r} (rE_r) = 0 \Rightarrow E_r = \frac{c}{r} \]  \hspace{1cm} (4-15)

Next we need to determine the constant c. This is easily done using Equation 4-7 with cylindrical coordinates:

\[ \int_a^b E_r dr = c \ln r|^b_a = V \Rightarrow c = \frac{V}{\ln(b/a)} \]  \hspace{1cm} (4-16)
So that the equation for the electric field in the resistive media becomes:

\[ E_r = \frac{V}{r \ln(b/a)} \]  \hspace{1cm} (4-17)

Much like the parallel plate capacitor, the cylindrical capacitor has the same electric field distribution as the cylindrical resistor. Figure 4-3 shows the strength of the electric field at different locations within the resistive/capacitive media. The radius of the media ranges from 0.0175 to 0.0215 meters. The five supply voltages are 30,000, 25,000, 20,000, 10,000 and 5,000 volts. The y-axis is in volts/meter.

![Figure 4-3 Electric field strength for cylindrical electrode geometry at various applied voltage levels.](image)

Figure 4-3 Electric field strength for cylindrical electrode geometry at various applied voltage levels.
4.3 Electric Field in a Series Lossy Media

In the previous sections we have studied the electric field in resistors and capacitors. In addition, we have found that the electric field does change when we vary the media in between the electrodes. In this section, we will study the electric field in materials that are described as both capacitive and resistive. Such materials are called lossy media. Lossy media can be thought of as a material that is initially similar to a capacitor. Over time, however, some of the energy it stores is lost. The energy storage loss in the capacitor is accounted for in the small amount of conductance the capacitor may have. More importantly, we will be studying lossy systems with multiple materials in various geometries separating the electrodes. For series lossy capacitors, we will need to introduce boundary conditions to solve Gauss’s equation. We will notice that in a series lossy capacitor the relative permittivity and conductivity will help to determine the electric field strength.

As mentioned in the previous paragraph, lossy systems are essentially capacitors that loose charge over time due to their slight conductivity. A simple diagram of a series lossy capacitor with two types of materials in between the electrodes can be seen in Figure 4-4. It is evident that the diagram is both capacitive and resistive.
Figure 4-4 Circuit diagram of series lossy capacitor.

Since the system is capacitive the characteristics of the electric field will vary with time. For this reason, we will study the systems at both time \( t = 0 \) and time \( t = \infty \). We will notice that at time \( t = 0 \) the surface charge at the interface where the two capacitive materials meet will be zero. We should also note that at time zero the system acts as a pure capacitor and current will flow freely, thus permittivity will be the controlling factor. With no surface charge density, the field is continuous across the interface so that:

\[
\varepsilon_1 E_1 = \varepsilon_2 E_2 \tag{4-18}
\]

This condition will help us to solve the electric field equation at time zero.

For time \( t = \infty \) after the voltage has been on for a long time the fields will reach their steady-state values. We should also note that, at time infinity, the system is fully charged and the capacitors will no longer pass current. Current will only be flowing through the resistors due to the lossy characteristic of the system, thus conductivity will be the controlling factor. Since there are no more time variations,
the current density must be continuous across the interface and the interface will be such that:

\[ \sigma_1 E_1 = \sigma_2 E_2 \]  
(4-19)

4.3.1 Electric Field at Time \( t = 0 \) in Parallel Plate Series Lossy Media

The first case we will study of lossy systems is the parallel plate design with multiple materials in between the electrodes. At time \( t = 0 \) the parallel plate series lossy capacitor will have the charges as seen in Figure 4-5 where the positive plate has a net positive charge and the negative electrode has a net negative charge.

![Figure 4-5 Parallel plate series lossy capacitor at time \( t = 0 \)](image)

We will use the voltage constraint to solve for the electric field in materials (1) and (2). We simply take the integral of the electric field and set it equal to the voltage drop across the electrodes.

\[ \int_{0}^{a+b} E_x \, dx = E_1 a + E_2 b = V \]  
(4-20)
Using constraint Equation 3-18 where at time \( t = 0 \) the surface charge density is zero, we find that:

\[
E_1 = \frac{\varepsilon_2 V}{\varepsilon_2 a + \varepsilon_1 b} \quad \text{and} \quad E_2 = \frac{\varepsilon_1 V}{\varepsilon_2 a + \varepsilon_1 b}
\]  

(4-21)

Table 4-4 shows the electric field strength for 30,000, 25,000, 20,000, 10,000, and 5,000 volts, at time \( t = 0 \). Material (1) is a dielectric material with a dielectric constant of 7 and a thickness of 0.004 meters. Material (2) is pure water with a dielectric constant of 80 and a thickness of 0.0341 meters. Additional material dielectric constants, also called the relative permittivity, can be seen in Table 4-1.

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>Electric Field ( (E_1) ) in Kynar (volts/m)</th>
<th>Electric Field ( (E_2) ) in Water (volts/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thickness (a) = .004 meters</td>
<td>Thickness (b) = .0341 meters</td>
</tr>
<tr>
<td>30,000</td>
<td>4,295,686</td>
<td>375,873</td>
</tr>
<tr>
<td>25,000</td>
<td>3,579,739</td>
<td>313,227</td>
</tr>
<tr>
<td>20,000</td>
<td>2,863,791</td>
<td>250,582</td>
</tr>
<tr>
<td>10,000</td>
<td>1,431,895</td>
<td>125,291</td>
</tr>
<tr>
<td>5,000</td>
<td>715,948</td>
<td>62,645</td>
</tr>
</tbody>
</table>

4.3.2 Electric Field at Time \( t = \infty \) in Parallel Plate Series Lossy Media

The electric field for the case at time \( t = \infty \) will differ since the system is fully charged. The charge on the material interface at time infinity will differ from that of
time 0 as seen in Figure 4-6. Material (1) will have a net negative charge at the interface and thus this will induce a net positive charge at the interface in material (2).

![Figure 4-6 Parallel plate series lossy capacitor at time t = ∞](image)

As mentioned earlier, the charged system will be loosing some charge due to its slight conductivity and thus the constraint Equation 4-19 will be used in conjunction with Equation 4-20. The result will be Equation 4-22 as seen below.

\[ E_1 = \frac{\sigma_2 V}{\sigma_2 a + \sigma_1 b} \quad \text{and} \quad E_2 = \frac{\sigma_1 V}{\sigma_2 a + \sigma_1 b} \] (3-22)

Table 4-5 shows the electric field strength for 30,000, 25,000, 20,000, 10,000, and 5,000 volts, at time \( t = \infty \). Once again, material (1) is a dielectric material with a conductivity of \( 5 \times 10^{-13} \) \( \text{Ω}^{-1} \text{m}^{-1} \) and a thickness of 0.004 meters. Material (2) is cooling water with a conductivity of 0.21 \( \text{Ω}^{-1} \text{m}^{-1} \) and a thickness of 0.0341 meters. Additional material conductivities can be seen in Table 4-2.
Table 4-5 Electric Field at time $t = \infty$ in Series Lossy Capacitor at various voltages and constant thickness.

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>Electric Field ($E_1$) in Kynar (volts/m)</th>
<th>Thickness (a) = .004 meters</th>
<th>Electric Field ($E_2$) in Water (volts/m)</th>
<th>Thickness (b) = .0341 meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>30,000</td>
<td>7,500,000</td>
<td></td>
<td>0.0000179</td>
<td></td>
</tr>
<tr>
<td>25,000</td>
<td>6,250,000</td>
<td></td>
<td>0.0000149</td>
<td></td>
</tr>
<tr>
<td>20,000</td>
<td>5,000,000</td>
<td></td>
<td>0.0000119</td>
<td></td>
</tr>
<tr>
<td>10,000</td>
<td>2,500,000</td>
<td></td>
<td>0.0000060</td>
<td></td>
</tr>
<tr>
<td>5,000</td>
<td>1,250,000</td>
<td></td>
<td>0.0000030</td>
<td></td>
</tr>
</tbody>
</table>

4.3.3 Electric Field at Time $t = 0$ in a Cylindrical Series Lossy Media

We will now study the series lossy media case for which the geometry is cylindrical. This will best represent the geometry of the electrostatic water treatment device used for experimentation at Lehigh University. For all practical purposes, the material thicknesses and properties will also be the same as what is seen in the experiments conducted at Lehigh University. Although, we will be most interested in the time infinity case, which will be presented in the next section. At time zero the cylindrical geometry charges are as seen in Figure 4-7.
Figure 4-7 Cylindrical series lossy capacitor at time $t = 0$

To solve for the electrostatic field equations we will use the voltage constraint across materials (1) and (2). We simply take the integral of the electric field and set it equal to the voltage drop across the electrodes:

$$\int_{a}^{b} E_r dr + \int_{b}^{c} E_r dr = V$$  \hspace{1cm} (4-23)

From the results of Equation 4-15 we can then find that:

$$\int_{a}^{b} \frac{c_1}{r} dr + \int_{b}^{c} \frac{c_2}{r} dr = V$$  \hspace{1cm} (4-24)

The solution to this integral becomes:

$$c_1 \ln \left( \frac{b}{a} \right) + c_2 \ln \left( \frac{c}{b} \right) = V$$  \hspace{1cm} (4-25)
Now we need to solve for the constants of integration. To do this we use Equation 4-15 and find that:

\[ E_1 = \frac{c_1}{r}, R_a < r < R_b \quad \text{and} \quad E_2 = \frac{c_2}{r}, \quad R_b < r < R_e \]  \hspace{1cm} 4-26

Using Equation 4-26, Equation 4-25 simplifies to:

\[ E_1 r \ln \left( \frac{b}{a} \right) + E_2 r \ln \left( \frac{c}{b} \right) = V \]  \hspace{1cm} 4-27

Since we know that at time \( t = 0 \) there is no surface charge density we can use Equation 4-18 and solve for \( E_1 \) and \( E_2 \). We find that:

\[ E_1 = \frac{1}{r} \frac{\varepsilon_2 V}{\varepsilon_2 \ln \left( \frac{b}{a} \right) + \varepsilon_1 \ln \left( \frac{c}{b} \right)} \]
\[ E_2 = \frac{1}{r} \frac{\varepsilon_1 V}{\varepsilon_2 \ln \left( \frac{b}{a} \right) + \varepsilon_1 \ln \left( \frac{c}{b} \right)} \]  \hspace{1cm} 4-28

Now that we have the equations for the electric field we can use them to determine the electric field in the different materials. Once again we will use the materials and material thicknesses that are used in the electrostatic water treatment device at Lehigh University. Our positively charged center aluminum electrode will have a radius (a) of 0.0175 meters. Material (1), dielectric material, will have a radius (b) of 0.0215 meters and a dielectric constant of 7. Material (2), pure water, will have a radius (c) of 0.0556 meters and a dielectric constant of 80. Using supply voltages of 30,000, 25,000, 20,000, 10,000 and 5,000 we get the electric field in the
dielectric material as seen in Figure 4-8 and the electric field in the water as seen in Figure 4-9.

![Figure 4-8 Electric field in dielectric material at Time t = 0](image)

Figure 4-8 Electric field in dielectric material at Time t = 0
Figure 4-9 Electric Field in Water at Time t = 0

As can be seen at time 0, the electric field is relatively large through the dielectric material and water. It can also be seen that the electric field in the water drops off very rapidly as you get further away from the positive electrode. As mentioned earlier, the case for time zero is interesting but does not best represent the field generated by the electrostatic water treatment device at Lehigh University. In addition, the permittivity value used was that of pure water and not that of water as seen in the experiments at Lehigh University. The permittivity is difficult to determine and; therefore, would explain the substitution. Fortunately, the time infinity case, which will be seen next, will best represent the field generated at Lehigh University. In addition, all of the values used in the infinity case will accurately represent the values used in experimentation at Lehigh University.
4.3.4 Electric Field at Time $t = \infty$ in a Cylindrical Series Lossy Media

We will now study the electric field in a series lossy media for the time infinity. As mentioned, the time infinity case is most important to us since it simulates the field that is distributed in the electrostatic water treatment device used for experimentation at Lehigh University. The electric field equations for a cylindrical geometry at time infinity are very similar to the time zero case. As seen in Figure 4-10, there is a net positive charge on the inside wall closest to the positive electrode of material (1) and a net negative charge on the inside wall of material (1) closest to material (2). Material (2) has a net negative charge on the surface closest to the negative electrode.

![Figure 4-10 Cylindrical series lossy capacitor at time $t = \infty$](image)

The process to solve the electric field equations at time infinity is very similar to that of time zero. We will use Equations 4-23 to 4-27 to get an equation in terms of $E_1$ and $E_2$. Then we obtain an equation in terms of only $E_1$ or $E_2$ by using Equation
4-19. Equation 4-19 describes the material interface characteristics at time $t = \infty$. We are then left with the electric field equations at time $t = \infty$:

\[ \begin{align*}
E_1 &= \frac{1}{r} \left( \frac{\sigma_2 V}{\sigma_2 \ln\left(\frac{b}{a}\right) + \sigma_1 \ln\left(\frac{c}{b}\right)} \right) \quad \text{and} \quad E_2 = \frac{1}{r} \left( \frac{\sigma_1 V}{\sigma_2 \ln\left(\frac{b}{a}\right) + \sigma_1 \ln\left(\frac{c}{b}\right)} \right)
\end{align*} \quad (4-29) \]

As seen, conductivity is used in these electric field equations since at time infinity we use Equation 4-19. Now that we have the equations for the electric field we can use them to determine the electric field in the different materials. Once again we will use the materials and material thicknesses that are used in the electrostatic water treatment device at Lehigh University. Our positively charged center aluminum electrode will have a radius $(a)$ of 0.0175 meters. Material (1), dielectric material, will have a radius $(b)$ of 0.0215 meters and a conductivity of $5 \times 10^{-13} \, \text{S/m}$. Material (2), cooling water, will have a radius $(c)$ of 0.0556 meters and a conductivity of $.21 \, \text{S/m}$. Using supply voltages of 30,000, 25,000, 20,000, 10,000 and 5,000 we get the electric field in the dielectric material as seen in Figure 4-11 and the electric field in the cooling water as seen in Figure 4-12.
Figure 4-11 Electric field in dielectric material at Time \( t = \infty \)

Figure 4-12 Electric Field in Cooling Water at Time \( t = \infty \)
Notice in this case at time $t = \infty$ that the electric field in the water has dropped considerably and that the electric field in the dielectric material remains high. This is due to the high resistivity of the dielectric material. Essentially, all of the voltage is used in the highly resistive dielectric material and there is very little voltage left to travel through the conductive cooling water.

4.4 Comparison of Electric Fields In Cooling Water for Parallel Plate Lossy Media and Cylindrical Geometry Lossy Media at Time Infinity

This section presents a comparison of the electric field strengths for parallel plate lossy media and cylindrical geometry lossy media. The comparison will be for the electric field in cooling water at time infinity. The values are taken from the calculations supplied in Sections 4.3.2 and 4.3.4. The comparison will be for multiple supply voltages; 30,000, 25,000, 20,000, 10,000 and 5,000. The value of the electric field will be taken at multiple distances away from the electrode. The comparisons can be seen in Tables 4-6 to 4-10.

**Table 4-6 Comparison of Electric Field at Multiple Locations in a Parallel Plate Lossy Media to that of Cylindrical Geometry (30,000 V Supply)**

<table>
<thead>
<tr>
<th>Distance in Water (m)</th>
<th>Cylindrical Volts/m</th>
<th>Parallel Volts/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0000161</td>
<td>0.0000179</td>
</tr>
<tr>
<td>0.0115</td>
<td>0.0000105</td>
<td>0.0000179</td>
</tr>
<tr>
<td>0.023</td>
<td>0.0000078</td>
<td>0.0000179</td>
</tr>
<tr>
<td>0.0341</td>
<td>0.0000063</td>
<td>0.0000179</td>
</tr>
</tbody>
</table>
Table 4-7 Comparison of Electric Field at Multiple Locations in a Parallel Plate Lossy Media to that of Cylindrical Geometry (25,000 V Supply)

<table>
<thead>
<tr>
<th>Distance in Water (m)</th>
<th>Cylindrical volts/m</th>
<th>Parallel volts/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0000134</td>
<td>0.0000149</td>
</tr>
<tr>
<td>0.0115</td>
<td>0.0000088</td>
<td>0.0000149</td>
</tr>
<tr>
<td>0.023</td>
<td>0.0000065</td>
<td>0.0000149</td>
</tr>
<tr>
<td>0.0341</td>
<td>0.0000052</td>
<td>0.0000149</td>
</tr>
</tbody>
</table>

Table 4-8 Comparison of Electric Field at Multiple Locations in a Parallel Plate Lossy Media to that of Cylindrical Geometry (20,000 V Supply)

<table>
<thead>
<tr>
<th>Distance in Water (m)</th>
<th>Cylindrical volts/m</th>
<th>Parallel volts/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0000108</td>
<td>0.0000119</td>
</tr>
<tr>
<td>0.0115</td>
<td>0.0000070</td>
<td>0.0000119</td>
</tr>
<tr>
<td>0.023</td>
<td>0.0000052</td>
<td>0.0000119</td>
</tr>
<tr>
<td>0.0341</td>
<td>0.0000042</td>
<td>0.0000119</td>
</tr>
</tbody>
</table>

Table 4-9 Comparison of Electric Field at Multiple Locations in a Parallel Plate Lossy Media to that of Cylindrical Geometry (10,000 V Supply)

<table>
<thead>
<tr>
<th>Distance in Water (m)</th>
<th>Cylindrical volts/m</th>
<th>Parallel volts/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0000054</td>
<td>0.000006</td>
</tr>
<tr>
<td>0.0115</td>
<td>0.0000035</td>
<td>0.000006</td>
</tr>
<tr>
<td>0.023</td>
<td>0.0000026</td>
<td>0.000006</td>
</tr>
<tr>
<td>0.0341</td>
<td>0.0000021</td>
<td>0.000006</td>
</tr>
</tbody>
</table>
Table 4-10  Comparison of Electric Field at Multiple Locations in a Parallel Plate Lossy Media to that of Cylindrical Geometry (5,000 V Supply)

<table>
<thead>
<tr>
<th>Distance in Water (m)</th>
<th>5,000 Volt Supply</th>
<th>Cylindrical volts/m</th>
<th>Parallel volts/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.00000027</td>
<td>0.000003</td>
<td></td>
</tr>
<tr>
<td>0.0115</td>
<td>0.0000018</td>
<td>0.000003</td>
<td></td>
</tr>
<tr>
<td>0.023</td>
<td>0.0000013</td>
<td>0.000003</td>
<td></td>
</tr>
<tr>
<td>0.0341</td>
<td>0.0000010</td>
<td>0.000003</td>
<td></td>
</tr>
</tbody>
</table>

As can be seen, the parallel plate lossy media maintains a constant electric field, whereas the cylindrical geometry lossy media has a diminishing electric field. In general, when comparing parallel and cylindrical lossy media at time infinity with similar material dimensions, the parallel plate case will have a larger electric field value.
CHAPTER 5: Experimental Studies on the Effects of Electrostatic Water Treatment on Scale Growth and Removal

This chapter reviews the experiments that were completed on the effects of electrostatic water treatment on calcium carbonate scale growth and removal. In order to study these effects, a test apparatus was built to partially simulate an industrial system. Heat transfer chambers were built to provide a location for calcium carbonate deposition to be monitored. The effects of electrostatic water treatment on both particulate and crystallization fouling were studied. In addition, studies were completed using both copper and stainless steel heat transfer surfaces.

Multiple parameters were monitored; including, water chemistry, flow velocities and water temperatures. Experiments were completed with and without electrostatic water treatment. This allowed for comparisons and in effect validates or invalidates the effectiveness of electrostatic water treatment.

5.1 Description of Test Apparatus

The test apparatus was built to analyze the effects of electrostatic water treatment on calcium carbonate deposition. Ideally the system was designed to simulate an industrial water system. The re-circulating tests apparatus can be seen in Figure 5-1. The premise of the design was to simulate the deposition of deposit on a heat exchanger. Cold water was flowing on top of a heated plate that was heated by hot water. The cold water contained high levels of dissolved solids, which in effect, when passing over a heated plate caused these dissolved solids to foul.
Figure 5-1 Test apparatus built at Lehigh University to measure the effects of electrostatic water treatment on the effects of calcium carbonated deposition.

5.1.1 Components of Test Apparatus

As seen, the test apparatus consisted of multiple parallel-flow plate heat exchanger chambers where calcium carbonate deposition were monitored. The inner cavity, where water was allowed to flow, had a width of 3.8 cm, a length of 8.9 cm, and a depth of 2.5 cm. The chambers were sealed with two rubber gaskets and were fastened with 8 bolts. The chambers were also fixed with a Plexiglas window so that
scale deposition would be monitored. The construction of the heat exchanger chamber can be seen in Figure 5-2.

![Figure 5-2 Schematic of parallel-flow, plate heat exchanger](image)

Hot water with temperatures up to 82°C was allowed to flow on the hot side of the heat exchanger and cold water with temperatures as low as 18°C was allowed to flow on the deposit side. In order to heat the water on the hot side a conventional electric hot water heater was used.

Water temperatures were measured on the hot and cold side, directly before and after each heat exchanger. All temperatures were measured with Omega K-type thermocouples and read on a hand held digital meter, model # HH501DK.

Since the cold water was heated by the hot water a cooling tower was needed. Water was allowed to flow in the top of the cooling tower and into the sump. The
cooling tower had a height of 1.06 m and a diameter of 0.26 m. The sump was
designed to contain a constant 95 liters.

The cooling tower was built in conjunction with a fan to aid in the cooling of
the water. The fan was rated to 550 CFM. Air was drawn from the base of the
cooling tower and out the top of the cooling tower.

Since the cooling effect causes evaporation, a float valve was installed in the
sump and water was replaced if the level dropped below a specified level. Magnetic
drive centrifugal pumps were used to pump the hot and cold water. The pumps were
rated at 30 liters/minute. Rotameter style flow meters were used to measure the
volumetric flow of water on the hot side and the cold side. The rotameters were rated
to 19 liters/minute. Most piping consisted of ¾” PVC piping.

The electrostatic water treatment device used is a side stream style with an
aluminum electrode radius of 0.0175 m. The electrode was coated with a dielectric
material with a dielectric constant of 7 and a conductivity $5 \times 10^{-13}$ Ψ/m and a radius
of 0.0215 m. The total electrostatic rod length was 0.63 m. The reaction chamber
was made of stainless steel with a radius of 0.0556 m. The electrostatic water
treatment device was powered with a Bertan series 230 voltage supply that was
capable of 30,000V.

5.1.2 Description of Deposit Plates

The deposit plates used were made of copper and stainless steel. Copper
plates were used initially but were later replaced with stainless steel. The
replacement was considered necessary after it was determined that copper (II) ions
may inhibit calcium carbonate scale growth [43,44]. The copper plates had a length of 9.6 cm, a width of 4.5 cm, and thickness of 0.762 mm. The stainless steel plates had length of 9.6 cm, a width of 4.5 cm, and a thickness of 0.533 mm. Most manufacturers of electrostatic water treatment claim that all components must be electrically grounded for electrostatic water treatment to be effective. Some of the plates were electrically grounded, therefore, in order to determine if it would have an effect on the deposition of calcium carbonate.

5.2 Test Method

All experiments were conducted using Bethlehem City tap water. Before chemicals could be added to the cold loop side, the Bethlehem water had to be tested for total hardness, calcium hardness, chloride, pH and conductivity. These values were then used in conjunction with the Langlier Scaling Index (LSI) to determine the scaling probability. It was determined that the LSI for Bethlehem tap water was \(-2.73\), which is very soft and has a high tendency to dissolve scale. It was determined that chemicals would need to be added in order to raise the LSI. The addition of chemicals to the Bethlehem tap water was complex and varied with the types of fouling desired. Once the chemicals were added the experiment could begin.

The Langlier Scaling Index was used throughout the experiments to monitor scaling probability. The use of the LSI required the measurement of calcium hardness, alkalinity, pH, conductivity and water temperature. The cold water temperature was used in the calculation of the LSI. Conductivity, which is closely related to TDS was used in the calculation of the LSI. In addition to the values used
in the LSI, total hardness and chloride were also measured. The levels of pH were measured using a pH tester model pHtestr 2 purchased from Fisher Scientific. The levels of conductivity were measured using a TDS tester model TDSTestr 20 purchased from Fisher Scientific. The levels of calcium hardness, total hardness, alkalinity and chloride were measured with titration techniques using digital titration and reagents purchased from Hach Company. The exact details of the chemical preparation of water chemistry will be discussed later.

During the experiments the flow rates and temperatures of the hot and cold side were measured. Once again, these values were varied from one experiment to another and will be discussed in greater detail. After each experiment the systems would be cleaned. This process is also complex and will be discussed later in detail.

5.2.1 The Addition of Chemicals to Achieve Required Sump Chemistry

As mentioned earlier, crystallization and precipitate fouling were studied and will both require a separated chemical addition process. In addition, crystallization fouling was studied with and without the addition of sodium carbonate. As a result, three separate chemical addition operations were utilized and will be clarified in detail. Each experiment will be presented in detail with and explanation of the types of fouling that were studied. In order to properly monitor the addition of chemicals and maintain levels of chemistry, many parameters were measured.
5.2.1.1 Chemicals Added to Achieve Crystallization Fouling

The bulk sump water in crystallization fouling should only contain dissolved ions. The first step of this process was to add 89 liters of water to the sump. The system was turned on and allowed to circulate with heat exchangers and blank heat exchanger plates in place. The hot water pump was not turned on and hot water was not allowed to circulate until the chemicals were completely added. After the water was added to the sump, 63.0 grams of Calcium Chloride (CaCl₂) were added to 2000 ml of tap water in a beaker. The water and the CaCl₂ were stirred with a magnetic stirrer until completely dissolved. The dissolved contents were slowly added to the circulating sump. Next, 48.0 grams of Sodium Bicarbonate (NaHCO₃) were added to 2000 ml of tap water in a beaker. The water and the NaHCO₃ were stirred with a magnetic stirrer until completely dissolved. The dissolved contents were then slowly added to the circulating sump. Lastly, 142.0 grams of Magnesium Sulfate (MgSO₄) were added to 2000 ml of tap water in a beaker. The water and the MgSO₄ were stirred with a magnetic stirrer until completely dissolved. The dissolved contents were then slowly added to the circulating sump. After all chemicals were added the sump contained 95 liters of water.

In order to insure that all chemicals were added properly the levels of calcium hardness, total hardness, alkalinity, chloride, pH and conductivity were measured and compared to a base test. A table of typical chemistry levels can be seen below in Table 5-1.
Once it was determined that the chemistry levels were suitable to run an experiment the hot water pump was started. The flowing of hot water then heated the heat exchanger plate and calcium carbonate crystallization was able to begin on the cold water side. Chemistry levels were then measured on daily basis.

### 5.2.1.2 Chemicals Added with the addition of Sodium Carbonate to Achieve Crystallization Fouling

The bulk sump water in this particular type of crystallization fouling should only contain dissolved ions. The first step of this process was to add 87 liters of water to the sump. The system was turned on and allowed to circulate with heat exchangers and blank heat exchanger plates in place. The hot water pump was not turned on and hot water was not allowed to circulate until the chemicals were completely added.

After the water was added to the sump, 63.0 grams of Calcium Chloride (CaCl₂) were added to 2000 ml of tap water in a beaker. The water and the CaCl₂ were stirred with a magnetic stirrer until completely dissolved. The dissolved contents were slowly added to circulating sump. Next, 142.0 grams of Magnesium Sulfate (MgSO₄) were added to 2000 ml of tap water in a beaker. The water and the MgSO₄ were stirred with a magnetic stirrer until completely dissolved. The dissolved contents were then
slowly added to the circulating sump. The levels of calcium hardness, total hardness, alkalinity, pH and conductivity were measured after the addition of these two chemicals.

After the addition of calcium chloride and magnesium sulfate the addition of the Sodium Bicarbonate (NaHCO₃) and Sodium Carbonate (Na₂CO₃) was completed in five steps. After each step the calcium hardness, total hardness, alkalinity, pH and conductivity were measured. The first step consisted of adding 20.0 grams NaHCO₃ to 2000 ml of tap water in a beaker. The water and the NaHCO₃ were stirred with a magnetic stirrer until completely dissolved. The dissolved contents were slowly added to the circulating sump. This completed step one and the chemistry of the water was then taken. Next, 23.0 grams of NaHCO₃ and 5.0 grams of Na₂CO₃ were added to 2000 ml of tap water in a beaker. The contents were stirred until completely dissolved. The water was then added to the sump 500 ml at a time in four steps, each an hour apart. After each of the four steps the calcium hardness, total hardness, alkalinity, pH and conductivity were measured, thus completing steps 2-5.

In order to insure that all chemicals were added properly the levels of calcium hardness, total hardness, alkalinity, chloride, pH and conductivity were compared to a base test. A table of typical chemistry levels can be seen below in Table 5-2.
Table 5-2 Typical chemistry levels for the preparation of crystallization fouling with the addition of Na$_2$CO$_3$

<table>
<thead>
<tr>
<th>Calcium Hardness (mg/L)</th>
<th>Total Hardness (mg/L)</th>
<th>Alkalinity (mg/L)</th>
<th>pH</th>
<th>Conductivity (µS/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>142 g of MgSO$_4$ and 63 g of CaCl$_2$</td>
<td>450</td>
<td>1100</td>
<td>8</td>
<td>7.4</td>
</tr>
<tr>
<td>20 g of NaHCO$_3$</td>
<td>450</td>
<td>1100</td>
<td>105</td>
<td>8</td>
</tr>
<tr>
<td>5.75 g of NaHCO$_3$ and 1.25 g of Na$_2$CO$_3$</td>
<td>455</td>
<td>1100</td>
<td>142</td>
<td>8.4</td>
</tr>
<tr>
<td>5.75 g of NaHCO$_3$ and 1.25 g of Na$_2$CO$_3$</td>
<td>450</td>
<td>1100</td>
<td>182</td>
<td>8.6</td>
</tr>
<tr>
<td>5.75 g of NaHCO$_3$ and 1.25 g of Na$_2$CO$_3$</td>
<td>455</td>
<td>1100</td>
<td>216</td>
<td>8.7</td>
</tr>
<tr>
<td>5.75 g of NaHCO$_3$ and 1.25 g of Na$_2$CO$_3$</td>
<td>455</td>
<td>1090</td>
<td>262</td>
<td>8.8</td>
</tr>
</tbody>
</table>

Once it was determined that the chemistry levels were suitable to run an experiment the hot water pump was started. The flowing of hot water then heated the heat exchanger plates and calcium carbonate crystallization could begin on the cold water side. Chemistry levels were then measured on daily basis.

5.2.1.3 Chemicals Added to Achieve Particulate Fouling

The bulk sump water in particulate fouling can contain both dissolved ions and solid calcium carbonate particles. The goal in the addition of these chemicals was to obtain some degree of free floating particles. The first step of this process was to add 87 liters of water to the sump. The system was turned on and allowed to circulate with heat exchangers and blank heat exchanger plates in place. The hot water pump was not turned on and hot water was not allowed to circulate until the chemicals were completely added. Next, 63.0 grams of Calcium Chloride (CaCl$_2$) were added to a 2000 ml of tap water in a beaker. The water and the CaCl$_2$ were
stirred with a magnetic stirrer until completely dissolved. The dissolved contents were slowly added to circulating sump. Next, 142.0 grams of Magnesium Sulfate (MgSO₄) were added to 2000 ml of tap water in a beaker. The water and the MgSO₄ were stirred with a magnetic stirrer until completely dissolved. The dissolved contents were then slowly added to the circulating sump. The levels of calcium hardness, total hardness, alkalinity, pH and conductivity were measured after the addition of these two chemicals.

After the addition of calcium chloride and magnesium sulfate, the addition of the Sodium Bicarbonate (NaHCO₃) and Sodium Carbonate (Na₂CO₃) were added in five steps. After each step the calcium hardness, total hardness, alkalinity, pH and conductivity were measured. The first step consisted of adding 40.0 grams NaHCO₃ to 2000 ml of tap water in a beaker. The water and the NaHCO₃ were stirred with a magnetic stirrer until completely dissolved. The dissolved contents were slowly added to the circulating sump. This completed step one and the chemistry of the water was then taken. Next, 46.0 grams of NaHCO₃ and 10.0 grams of Na₂CO₃ were added to 2000 ml of tap water in a beaker. The contents were stirred until completely dissolved. The water was then added to the sump 500 ml at a time in four steps, each an hour apart. Each time the calcium hardness, total hardness, alkalinity, pH and conductivity were measured, thus completing steps 4-5.

In order to insure that all chemicals were added properly the levels of calcium hardness, total hardness, alkalinity, chloride, pH and conductivity were compared to a base test. A table of typical chemistry levels can be seen below in Table 5-3.
Typically, particles would not form in the sump for another 2 hours after the chemicals were added.

Table 5-3 Typical chemistry levels for the preparation of particulate fouling

<table>
<thead>
<tr>
<th>Chemicals</th>
<th>Calcium Hardness (mg/L)</th>
<th>Total Hardness (mg/L)</th>
<th>Alkalinity (mg/L)</th>
<th>pH</th>
<th>Conductivity (µS/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>142 g of MgSO₄ and 63 g of CaCl₂</td>
<td>430</td>
<td>1080</td>
<td>9.3</td>
<td>7.4</td>
<td>1743</td>
</tr>
<tr>
<td>40 g of NaHCO₃</td>
<td>440</td>
<td>1050</td>
<td>210</td>
<td>8</td>
<td>2110</td>
</tr>
<tr>
<td>11.5 g of NaHCO₃ and 2.5 g of Na₂CO₃</td>
<td>440</td>
<td>1060</td>
<td>294</td>
<td>8.4</td>
<td>2170</td>
</tr>
<tr>
<td>11.5 g of NaHCO₃ and 2.5 g of Na₂CO₃</td>
<td>435</td>
<td>1060</td>
<td>360</td>
<td>8.6</td>
<td>2240</td>
</tr>
<tr>
<td>11.5 g of NaHCO₃ and 2.5 g of Na₂CO₃</td>
<td>440</td>
<td>1070</td>
<td>432</td>
<td>8.7</td>
<td>2390</td>
</tr>
<tr>
<td>11.5 g of NaHCO₃ and 2.5 g of Na₂CO₃</td>
<td>440</td>
<td>1060</td>
<td>530</td>
<td>8.7</td>
<td>2490</td>
</tr>
</tbody>
</table>

Once it was determined that the chemistry levels were suitable to run an experiment the hot water pump was started. The flowing of hot water would then heat the heat exchanger plate and calcium carbonate crystallization could begin on the cold water side. Chemistry levels were then measured on daily basis.

5.2.2 Temperature Measurements

A total of four temperatures were monitored during the experiment. Two thermocouples were placed directly before and after the heat exchanger on the cold side of the loop. The other two thermocouples were placed directly before and after the heat exchanger on the hot side of the loop. For the first set of experiments the temperatures of the hot side were typically 60°C and the temperatures of the cold side were 21°C. It was later determined that the temperature of the hot side should be raised. In the second set of experiments the temperatures of the hot side were around
71°C and the temperatures of the cold side remained around 21°C. Due to the complexity, each experiment will be presented with the temperatures of water used.

5.2.3 Flow Measurements

A total of two flow rates were measured in the experiment. One rotameter was placed on the hot loop and another rotameter was placed on the cold loop. The volumetric flow rate of the water in the hot loop was 10.3 liters/minute. The flow rate on the cold loop was changed depending on the experiment. The first set of experiments consisted of three heat exchangers in parallel and the volumetric flow rate was 11.4 liters/minute. The average velocity of the cold water in one of the heat exchangers was thus 6.53 cm/s. The second set of experiments contained four heat exchangers in parallel and a volumetric flow rate of 6.1 liters/minute. The average velocity of the cold water in one of the heat exchangers was 2.64 cm/s.

5.2.4 Cleaning of the System

After the completion of each experiment the heat transfer plates were removed and the sump was completely emptied and filled with clean tap water. The heat transfer chambers were then connected to the system again but with false plates. The cold water pump was then turned on and sulfuric acid was then placed in the sump and stirred until a pH of 3.0 was reached. The sulfuric acid was added to dissolve any remaining calcium carbonate in the system. This insured that each experiment began with the same conditions. The pH was then monitored every fifteen minutes. As calcium carbonate was dissolved the pH rose. A rise in pH resulted in the addition of
more sulfuric acid. Once the pH remained steady for an hour the water was dumped and the system was flushed with clean tap water. The sump was filled once again and it was assured that the pH is 7.0, which matched the pH of Bethlehem tap water. The system was then ready for a new experiment.

5.2.5 Measurement of Scale Deposition

In order to compare the levels of scaling with and without water treatment measurement techniques needed to be developed to quantify the levels of scale deposition. It was determined that the mass of the plates would be the simplest and most useful means to quantify scale growth. The plates would be weighed before they were placed into the heat exchanger. After the experiment was complete the plates would be removed, dried and weighed again. The change in the mass would determine the amount of scale deposited. All plates were weighed on a digital scale, accurate to $10^{-4}$ grams or a mechanical scale, accurate to $10^{-5}$ grams.

The plates were also measured qualitatively. After each experiment the plates were examined and compared. Pictures were taken with a digital camera. The plates were also examined under an optical microscope. Although these photographs are useful they do not provide any conclusive qualitative data.

5.3 Results

Numerous tests were completed on the effects of electrostatic water treatment on the deposition of calcium carbonate. The first set of experiments examined the effects electrostatic water treatment has on crystallization fouling. All experiments
were compared to a control, where no treatment was used. These crystallization experiments were completed using grounded and ungrounded copper and stainless steel plates.

The second set of experiments examined the effects of electrostatic water treatment on particulate fouling. All experiments were compared to a control, where no treatment was used. These particulate fouling experiments were completed using grounded and ungrounded copper and stainless steel plates.

An experiment was also completed on the effects of electrostatic water treatment on calcium carbonate scale removal. Two non-treated stainless steel plates from the particulate fouling experiment were placed in heat exchanger chambers. In addition, two blank stainless steel plates were placed in the remaining two heat exchanger chambers. The water was prepared in a manner that would produce crystallization fouling. The system was turned on for three days and the amount of scale growth or removal was determined.

For each experiment the before and after mass of the heat transfer plates will be given. The value of the LSI will also be given for each experiment. The actual values describing the water chemistry present can be found in Appendix A.

5.3.1 The Studies of The Effects of Electrostatic Water Treatment on Crystallization Fouling

The first group of experiments compared the effects of electrostatic water treatment on crystallization fouling. The sump was prepared each time in a manner that would promote crystallization fouling. Three sets of experiments were
completed on crystallization fouling. The first set compared treated and untreated calcium carbonate in ungrounded copper plates. The second set of experiments compared treated and untreated calcium carbonate deposits on grounded copper plates. The last set of experiments compared treated and untreated, grounded and ungrounded, copper and stainless steel plates.

5.3.1.1 Comparison Between Untreated and Treated, Ungrounded Copper Plates Under Crystallization Fouling Conditions

The first set of experiments completed, test #1 and test #2 were for untreated and treated ungrounded copper plates. Test #1 was for untreated copper plates and test #2 was for treated copper plates. For both experiments, three new copper plates were prepared and carefully placed inside of three heat exchanger containers. The sump was then prepared for crystallization fouling. The system was turned on and the electrostatic water treatment was left off for test #1 and turned on for test #2. The hot water volumetric flow rate was 10.3 liters/minute and the average velocity in one of the chambers was 5.9 cm/s. The cold water volumetric flow rate was 11.4 liters/minute and the average velocity passing over each copper heat transfer plate was 6.53 cm/s. Temperatures on the cold loop inlet and outlet were maintained at about 20.5°C and 22.2°C respectively. Temperatures on the hot loop inlet and outlet were maintained at about 62.2°C and 60.0°C.

The experiment was run for a total of 168 hours. For the first 120 hours only CaCl₂ and MgSO₄ were added. At 120 hours the NaHCO₃ was added and scale began to form. Measurements of calcium hardness, total hardness, alkalinity, chloride, pH,
conductivity and temperature were taken on a daily basis and can be seen in detail in Appendix A. The value of the LSI for the treated and untreated experiment can be seen in Figure 5-3. As seen the LSI for each experiment follows roughly the same path.

Figure 5-3 The calculated LSI for the untreated and treated ungrounded copper systems

After the experiments were finished, the plates were weighed on a digital balance accurate to $10^{-4}$ grams. The amounts of calcium carbonate deposits were then calculated and compared to determine whether or not electrostatic water treatment had an effect on crystallization fouling. The untreated plates 1, 2 and 3 had 0.0702, 0.0613 and 0.0596 grams of calcium carbonate deposit, respectively. The treated plates 1, 2 and 3 had 0.0645, 0.0672 and 0.0677 grams of calcium carbonate deposit, respectively. The comparison can be seen in Figure 5-4. Upon inspection of the
graph it seems as though electrostatic water treatment has little effect on the calcium carbonate crystallization fouling on ungrounded copper plates.

![Comparison of calcium carbonate scale deposition by mass for treated and untreated plates](image)

**Figure 5-4 Comparison of calcium carbonate scale deposition by mass for treated and untreated plates**

The plates can also be qualitatively compared. Figure 5-5 shows a 100X magnification and a full view of an untreated copper plate and Figure 5-6 shows a 100X magnification and a full view of a plate after treatment.

**Figure 5-5 100X magnification and full view of untreated, ungrounded copper plates**
Upon visual inspection of the plates, very little variation in the texture and thickness of the calcium carbonated deposit can be determined.

5.3.1.2 Comparison Between Untreated and Treated, Grounded Copper Plates Under Crystallization fouling Conditions

The second set of experiments completed, test #3 and test #4 were for treated and untreated grounded copper plates. Test #3 was for treated copper plates and test #4 was for untreated copper plates. For both experiments, three copper plates were prepared and carefully placed inside of three heat exchanger containers. The sump was then prepared for crystallization fouling. The system was turned on and the electrostatic water treatment was turned on for test #3 and turned off for test #4. The hot water volumetric flow rate was 10.3 liters/minute and the average velocity in each of the chambers was 5.9 cm/s. The cold water volumetric flow rate 11.4 liters/minute and the average velocity passing over each copper heat transfer plate was 6.53 cm/s. Temperatures on the cold loop inlet and outlet were maintained at about 20.5°C and
22.2°C respectively. Temperatures on the hot loop inlet and outlet were maintained at about 62.2°C and 60.0°C.

The experiment was run for a total of 48 hours. Measurements of calcium hardness, total hardness, alkalinity, chloride, pH, conductivity and temperature were taken on a daily basis and can be seen in detail in Appendix A. The value of the LSI for the treated and untreated experiments can be seen in Figure 5-7. As seen, the LSI was roughly the same for each experiment.

![Figure 5-7 The calculated LSI for the untreated and treated copper grounded systems](image)

After the experiments were finished, the plates were weighed on a digital balance accurate to $10^{-4}$ grams. The amounts of calcium carbonate deposited were calculated and compared to determine whether or not electrostatic water treatment had an effect on crystallization fouling. The untreated plates 1, 2 and 3 had 0.0023, 0.0037 and 0.0030 grams of calcium carbonate deposit, respectively. The treated
plates 1, 2 and 3 had 0.0183, 0.0179 and 0.0006 grams of calcium carbonate deposit, respectively. The comparison can be seen in Figure 5-8. Upon inspection of the graph it seems as though electrostatic water treatment has little effect on the calcium carbonate crystallization fouling on grounded copper plates.

![Graph showing calcium carbonate deposition](image)

**Figure 5-8 Comparison of calcium carbonate crystallization scale deposition by mass for treated and untreated copper plates**

The plates can also be qualitatively compared. Figure 5-9 shows a 100X magnification and a full view of an untreated copper plate and Figure 5-10 shows a 100X magnification and a full view of a treated copper plates.
Upon visual inspection of the plates, very little variation in the texture and thickness of the calcium carbonated deposit could be determined between the treated and untreated conditions.

5.3.1.3 Comparison Between Untreated and Treated, Grounded and Ungrounded Stainless Steel Plates Under Crystallization Fouling Conditions

The third set of experiments completed, tests #5 and #6 were for untreated and treated grounded and ungrounded stainless steel plates. Test #5 was for untreated,
Upon visual inspection of the plates, very little variation in the texture and thickness of the calcium carbonated deposit could be determined between the treated and untreated conditions.

5.3.1.3 Comparison Between Untreated and Treated, Grounded and Ungrounded Stainless Steel Plates Under Crystallization Fouling Conditions

The third set of experiments completed, tests #5 and #6 were for untreated and treated grounded and ungrounded stainless steel plates. Test #5 was for untreated,
grounded and ungrounded stainless steel plates and test #6 was for treated, grounded and ungrounded stainless steel plates. For both experiments, four stainless steel plates were prepared and carefully placed inside of four heat exchanger containers. The sump was then prepared for crystallization fouling. The system was turned on and the electrostatic water treatment was left off for test #5 and turned on for test #6. The hot water volumetric flow rate was 10.3 liters/minute and the average velocity in each chamber was 4.4 cm/s. The cold water volumetric flow rate was 6.1 liters/minute and the average velocity passing over each stainless steel heat transfer plate was changed to 2.64 cm/s. Temperatures on the cold loop inlet and outlet were maintained at about 20.5°C and 22.2°C respectively. Temperatures on the hot loop inlet and outlet were maintained at about 71.1°C and 68.3°C. For both experiments, plates 1 and 3 were ungrounded and plates 2 and 4 were grounded.

The experiments were each run for a total of 96 hours. Measurements of calcium hardness, total hardness, alkalinity, chloride, pH, conductivity and temperature were taken on a daily basis and can be seen in detail in Appendix A. The value of the LSI for the treated and untreated experiments can be seen in Figure 5-11.
Figure 5-11 The calculated LSI for the untreated and treated grounded and ungrounded stainless steel systems with crystallization fouling

After the experiments were finished, the plates were weighed on a digital balance accurate to $10^{-4}$ grams. The amounts of calcium carbonate deposited were calculated and compared to determine whether or not electrostatic water treatment had an effect on crystallization fouling. The untreated plates 1, 2, 3 and 4 had 0.0225, 0.0075, 0.0034 and 0.0217 grams of calcium carbonate deposit, respectively. The treated plates 1, 2, 3 and 4 had 0.0031, 0.0339, 0.0030 and 0.0060 grams of calcium carbonate deposit, respectively. The comparison of these deposit amounts can be seen in Figure 5-12.
Figure 5-12 Comparison of calcium carbonate crystallization scale deposition by mass for treated and untreated stainless steel plates

Upon visual inspection it appeared that whether or not the plates were grounded had little effect on calcium carbonate scale deposition. In addition it appeared that electrostatic water treatment may have had a beneficial effect on plates 1 and 4 but not on 2 and 3.

The stainless steel plates were also analyzed qualitatively. Figure 5-13 shows the full view and the close-up view of an untreated, ungrounded stainless steel plate. The untreated, grounded stainless steel plates were very similar upon visual inspection. Figure 5-14 shows the full view and the close-up view of a treated, grounded stainless steel plate. Once again, the treated, ungrounded stainless steel plate is very similar upon visual inspection.
No noticeable difference was observed among the grounded and ungrounded, treated and untreated stainless steel calcium carbonate deposits.

5.3.2 The Studies of The Effects of Electrostatic Water Treatment on Particulate Fouling Deposit and Removal From Stainless Steel Plates

The second group of experiments compared the effects of electrostatic water treatment on particulate fouling on stainless steel plates. The sump was prepared each time in a manner that would promote particulate fouling. This group of
experiments compared treated, grounded and ungrounded plates to untreated
grounded and ungrounded plates.

The last experiment measured the effects of electrostatic water treatment on
particulate fouling scale removal. In this experiment two plates from the untreated
particulate fouling experiment were taken and placed in heat transfer chambers. The
water was prepared for crystallization fouling and the amount of scale removal or
growth was measured.

5.3.2.1 Comparison Between Untreated and Treated, Grounded and
Ungrounded Stainless Steel Plates Under Particulate Fouling Conditions

The fourth set of experiments completed, tests #7 and #8 were for treated and
untreated grounded and ungrounded stainless steel plates. Test #7 was for treated,
grounded and ungrounded stainless steel plates and test #8 was for untreated,
grounded and ungrounded stainless steel plates. For both experiments, four stainless
steel plates were prepared and carefully placed inside the four heat exchanger
containers. The sump was then prepared for particulate fouling. The system was
turned on and the electrostatic water treatment was turned on for test #7 and turned
off for test #8. The hot water volumetric flow rate was 10.3 liters/minute and the
average velocity in each chamber was 4.4 cm/s. The cold water volumetric flow rate
was 6.1 liters/minute and the average velocity passing over each stainless steel heat
transfer plate was 2.64 cm/s. Temperatures on the cold loop inlet and outlet were
maintained at about 20.5°C and 22.2°C respectively. Temperatures on the hot loop
inlet and outlet were maintained at about 71.1°C and 68.3°C. For both experiments, plates 1 and 3 were ungrounded and plates 2 and 4 were grounded.

Each experiment was run for a total of 36 hours. Measurements of calcium hardness, total hardness, alkalinity, chloride, pH, conductivity and temperature were taken on a daily basis and can be seen in detail in Appendix A. The value of the LSI for the treated and untreated experiments can be seen in Figure 5-15.

![Figure 5-15](image)

**Figure 5-15** The calculated LSI for the untreated and treated grounded and ungrounded stainless steel systems under particulate fouling conditions

After the experiments were finished, the plates were weighed on a digital balance accurate to $10^{-5}$ grams. The amounts of calcium carbonate deposited were calculated and compared to determine whether or not electrostatic water treatment had an effect on particulate fouling. The untreated plates 1, 2, 3 and 4 had 0.46100, 0.47334, 0.41022 and 0.43547 grams of calcium carbonate deposit, respectively. The
treated plates 1, 2, 3 and 4 had 0.44744, 0.44448, 0.37845 and 0.43564 grams of calcium carbonate deposit, respectively. The comparison of these calcium carbonate amounts can be seen in Figure 5-16.

Figure 5-16 Comparison of calcium carbonate particulate scale deposition by mass for treated and untreated stainless steel plates

Upon visual inspection it appeared that the grounded plates 1 and 3 and ungrounded plates 2 and 4 do not differ in the mass deposition of calcium carbonate. In addition it appeared that electrostatic water treatment did not under the conditions tested have an effect on particulate fouling.

The stainless steel plates were also analyzed qualitatively. Figure 5-17 shows a full view and a close-up view of an ungrounded, untreated stainless steel plate from test #8. As can be observed from the mass data the grounded, untreated stainless steel
plates displayed the same deposition characteristics. Figure 5-18 shows a full view and a close-up view of a grounded, treated stainless steel plate from test #7. Once again, the ungrounded, treated stainless steel plates displayed the same deposition characteristics.

Figure 5-17 Full view and close-up view of untreated, ungrounded stainless steel plate under particulate fouling

Figure 5-18 Full view and close-up view of treated, ungrounded stainless steel plate under particulate fouling

As was observed from visual inspection, there appeared to be no variation in the deposition of calcium carbonate for treated and untreated stainless steel plates.
5.3.2.2 The Effects of Electrostatic Water Treatment on the Removal of Calcium Carbonate Particulate Scale Deposition on Stainless Steel Plates

The last experiment, test #9, was completed to observe the effects of electrostatic water treatment on the removal of calcium carbonate. Two untreated, ungrounded plates (plates 1 and 3 from test #8) were placed in the heat transfer chambers. Plate #1 was grounded and plate #3 was ungrounded. Additionally, two blank stainless steel plates were placed in the other heat transfer chambers. Plate #2 was grounded and plate #4 was ungrounded. The sump was then prepared for crystallization fouling. The system was turned on and the electrostatic water treatment was left on. The hot water volumetric flow rate was 10.3 liters/minute and the average velocity in each chamber was 4.4 cm/s. The cold water volumetric flow rate was 6.1 liters/minute and the average velocity passing over each stainless steel heat transfer plate was changed to 2.64 cm/s. Temperatures on the cold loop inlet and outlet were maintained at about 20.5°C and 22.2°C respectively. Temperatures on the hot loop inlet and outlet were maintained at about 71.1°C and 68.3°C.

The experiment was run for a total of 96 hours. Measurements of calcium hardness, total hardness, alkalinity, chloride, pH, conductivity and temperature were taken on a daily basis and can be seen in detail in Appendix A. The value of the LSI for the treated and untreated experiment can be seen in Figure 5-19.
As mentioned, the plates 1 and 3 from experiment #8 were placed in the heat transfer chambers. The goal was to determine if particulate scale could be removed under normal crystallization fouling operating conditions.

![Diagram](image)

Figure 5-19 The calculated LSI for treated grounded and ungrounded stainless steel plates under crystallization fouling conditions

After the experiment was finished, the plates were weighed on a digital balance accurate to $10^{-5}$ grams. The amount of calcium carbonate removal or deposit was measured to determine if electrostatic water treatment had an effect on calcium carbonate scale removal. Plates 1 and 3, which started with a layer of particulate fouled calcium carbonate, increased in mass. The grounded plate 1 gained an additional 0.41862 grams and the ungrounded plate 3 gained an additional 0.34329 grams of calcium carbonate. The blank stainless steel plates 2 and 4 also increased in mass. The grounded plate 2 gained a total of 0.00800 grams and the ungrounded
plate 4 gained a total of 0.00718 grams of calcium carbonate. The results can be seen in Figure 5-20.

As seen, plates 1 and 3 gained more calcium carbonate scale than the blank plates 2 and 4. The difference can be accounted for in the difference in nucleation sites. The blank plates 2 and 4 had very little nucleation sites and plates 1 and 3 had a pre-existing layer of calcium carbonate, which aided in further deposits. It appears that electrostatic water treatment in the manner applied did not have an effect on particulate fouling deposit removal. In addition, it appears that grounding of the plates did not affect the deposition of calcium carbonate.

Figure 5-20 Levels of calcium carbonate scale removal or deposit from or on stainless steel plates under crystallization fouling conditions

As seen, plates 1 and 3 gained more calcium carbonate scale than the blank plates 2 and 4. The difference can be accounted for in the difference in nucleation sites. The blank plates 2 and 4 had very little nucleation sites and plates 1 and 3 had a pre-existing layer of calcium carbonate, which aided in further deposits. It appears that electrostatic water treatment in the manner applied did not have an effect on particulate fouling deposit removal. In addition, it appears that grounding of the plates did not affect the deposition of calcium carbonate.
Plate 1 can be observed qualitatively in Figure 5-21. Plate 1 was taken from test #8 and placed in experiment #9. The qualitative change in scale growth can be seen by comparing Figure 5-17 and Figure 5-21.

![Plate 1](image1)

**Figure 5-21 Full view and close-up view of grounded and treated plate 1 for measurement of the effects of electrostatic water treatment on calcium carbonate removal**

As seen, electrostatic water treatment under the conditions tested did not appear to have an effect on the removal of calcium carbonate scale.

### 5.4 Conclusions on the Effects of Electrostatic Water Treatment on Scale Growth and Removal

Conclusions can be made on the effectiveness of electrostatic water treatment on scale growth and removal for specific values of water temperature, chemistry, flow rates and materials used. The conclusions will be made based on the quantitative values of calcium carbonate scale deposited. Conclusions can also be made based on the qualitative data collected, but they are not as useful. Unfortunately, calcium carbonate deposits depend heavily on water temperatures, chemistry, flow rates and plate materials used. Therefore, absolute conclusions cannot be made until all of
these parameters are thoroughly studied in conjunction with electrostatic water treatment. Results for each set of experiments will be presented.

As mentioned earlier, tests #1 and #2 compared untreated and treated copper plates that were ungrounded under crystallization fouling conditions. The value of the LSI on average was 4.08% higher for the untreated test #1 than the treated test #2. The deposited mass of calcium carbonate on average was 4.35% lower for the untreated test #1 than the treated test #2. These values can be seen in Table 5-4.

Table 5-4 Comparison of average LSI and average deposited mass for untreated and treated, ungrounded copper plates under crystallization fouling conditions

<table>
<thead>
<tr>
<th>Treated</th>
<th>Untreated</th>
<th>% Difference</th>
<th>Treated</th>
<th>Untreated</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.41</td>
<td>1.47</td>
<td>4.08</td>
<td>0.06647</td>
<td>0.0637</td>
<td>-4.35</td>
</tr>
</tbody>
</table>

As seen, the average value of the LSI is higher for the untreated system, which should result in higher levels of calcium carbonate scale deposition. Despite this, however, the untreated system on average had less calcium carbonate deposition. This would lead one to believe that the electrostatic water treatment system was not effective under the test conditions used for tests #1 and #2.

Tests #3 and #4 compared the treated and untreated copper plates that were grounded under crystallization fouling conditions. The value of the LSI on average was 9.92% less for the treated test #3 than for the untreated test #4. The deposited
mass of calcium carbonate on average was 309.00 % lower for the untreated system than for the treated system. The comparison of these values can be seen in Table 5-5.

Table 5-5 Comparison of average LSI and average deposition mass for untreated and treated, grounded copper plates under crystallization fouling conditions

<table>
<thead>
<tr>
<th></th>
<th>Treated</th>
<th>Untreated</th>
<th>% Difference</th>
<th>Treated</th>
<th>Untreated</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSI</td>
<td>1.44</td>
<td>1.31</td>
<td>-9.92</td>
<td>0.01227</td>
<td>0.00300</td>
<td>-309.00</td>
</tr>
<tr>
<td>Deposition (g)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As seen the value of the LSI is on average higher for the treated system and the value of calcium carbonate is also higher for the treated system. One would expect that the higher value of LSI would result in a higher value of deposit. It is unknown whether or not a 9.92 % difference in the LSI would result in a 309.00 % difference in the deposition of calcium carbonate. Although, it is unlikely that the electrostatic water treatment as applied in the current case had any effect on the deposition of calcium carbonate for the conditions used in tests #3 and #4.

Tests #5 and #6 compared the untreated and treated stainless steel plates that were grounded and ungrounded under crystallization fouling conditions. The value of the LSI on average was 0.64 % less for the untreated test #5 than for the treated test #6. The deposited mass of calcium carbonate on average was 16.55 % higher for the untreated system than for the treated system. The comparison of these values can be seen in Table 5-6.
Comparing the LSI and the deposition percentage one notices that despite the higher susceptibility of the treated system to form calcium carbonate scale the mass percentage of calcium carbonate was on average lower for the treated system. One could conclude that electrostatic water treatment was in fact effective under the conditions studied in tests #5 and #6.

The test set of experiments, tests #7 and #8 studied the deposition of particulate fouling on treated and untreated, grounded and ungrounded stainless steel plates. The value of the LSI for the untreated system was on average 4.20% higher for the untreated test #8 than the treated test #7. The deposition mass for the untreated system was on average 4.34% lower for the untreated test #8 than the treated test #7. The comparison of these values can be seen in Table 5-7.
Despite the higher average value of LSI for the untreated system the average value of the deposited mass was higher for the treated system. This leads one to conclude that electrostatic water treatment as applied was not effective on the particulate fouling deposition for the conditions analyzed in test #7 and test #8.

The last experiment analyzed the effectiveness of electrostatic water treatment on the removal of particulate fouling on grounded and ungrounded stainless steel plates under crystallization fouling. As mentioned earlier, two blank plates were also placed in the experiment to compare the levels of calcium carbonate removal or deposit. As seen in Table 5-8 the average value of the LSI was 1.55 and both the pre-fouled plates and the blank plates increased in mass.

Table 5-8 Comparison of pre-fouled and blank stainless steel plates to measure the levels of calcium carbonate removal or deposition under treated and crystallization fouling conditions

<table>
<thead>
<tr>
<th>LSI</th>
<th>Deposition (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treated</td>
<td>Fouled</td>
</tr>
<tr>
<td>1.55</td>
<td>0.37996</td>
</tr>
</tbody>
</table>

The values seen in Table 5-8 leads one to conclude that electrostatic water treatment as applied did not have an effect on the removal of particulate fouled calcium carbonate under the conditions studied. The pre-fouled plates on average gained 98.00 % more scale than the blank plates. This is most likely due to the increase in nucleation sites on the pre-fouled stainless steel plates.
This chapter reviews the experiments that were completed on the effectiveness of electrostatic water treatment on calcium carbonate particle size. It has been proposed that the distributed electric field through flowing water will induce a negative like charge on free flowing particles. The negative charge on these particles could then prevent agglomeration and even perhaps reduce particle size. It is beneficial to maintain small particles, since it is known that larger particles settle and deposit more rapidly than smaller particles. Since particles and not ions in solution, were studied, any potential effects that electrostatic treatment may have on ions were not uncovered. As a result, the experiments do not shed light on the mechanism by which crystallization fouling may be affected by electrostatic water treatment. However, studying particle sized could shed some light on the mechanistic effect by which particulate fouling may be affected.

6.1 Description of Test Apparatus

The test apparatus built to analyze the effects of electrostatic water treatment on calcium carbonate particle size can be seen in Figure 6-1. The premise of the design was to simulate an industrial system. Calcium carbonate particles of a known size were mixed with water and allowed to flow through the electrostatic water treatment, simple piping system and sump.
As seen, there were four major components. These components are the water pump, sump, voltage supply and the electrostatic water treatment device. Water flowed from the sump, through the bottom of the electrostatic water treatment device and back into the sump. The sump was able to contain 60 liters of water. A lid was placed on top of the sump. The lid prevented objects from entering the sump but still allowed the system to breath. Water flowed through PVC pipes with an inner diameter of \( \frac{3}{4} \)”. The PVC piping that delivered water into the sump was designed in such a way to agitate and circulate water. The piping lied on the bottom of the sump tank. A top view of the piping system can be seen in Figure 6-2 where the blue arrows represent the flow of water exiting the piping system.
The pump used was a shaft driven centrifugal pump that is capable of delivering 28 liters/minute.

The electrostatic water treatment device used was a side stream style with an aluminum electrode radius of 0.0175 m. The electrode was coated with a dielectric material with a dielectric constant of 7 and a conductivity of $5 \times 10^{-13} \text{ S/m}$ and a radius of 0.0215 m. The total electrostatic rod length was 0.305 m. The reaction chamber was made of stainless steel with a radius of 0.0556 m. The electrostatic water treatment device was powered with a Bertan series 230 voltage supply that was capable of providing a pure 30,000 Volt D.C. voltage at current levels up to .2 mA.
6.2 Test Method

Experiments were run with and without electrostatic treatment in order to compare and evaluate the effect electrostatic water treatment has on calcium carbonate particle size. A total of three experiments were run. The first experiment, test #1 was run with treatment and without treatment and the time varying change of particle sizes were measured. Test #2 was run without treatment and test #3 was run with treatment. Calcium carbonate particle sizes were measured with a Coulter N4 particle size analyzer.

6.2.1 Addition of Calcium Carbonate

When testing for the effects of electrostatic water treatment on calcium carbonate particle size a series of steps need to be followed. First 60 liters of Bethlehem City tap water was added to the sump. The water was allowed to rise to between 20 °C and 22 °C or room temperature. The pump was then turned on and water flowed at a rate of 28 liters/minute.

For the first test, test #1, reagent grade calcium carbonate particles that were obtained from Fisher Scientific were used. A total of 5 grams of calcium carbonate was added to the system. These particles measured between 1970 nm and 2860 nm. It was determined that this range and size was unacceptable for the Coulter N4.

For the second and third tests, test #2 and test #3, the calcium carbonate particles that were added to the system were obtained from Specialty Minerals in Bethlehem, PA. For each experiment a total of 5 grams of calcium carbonate were added. These particles measured between 562 nm and 1570 nm. It was determined
that these particles were more suitable for the Coulter N4, but still in some cases still exceed the capabilities of the machine.

For test #1 the system was run for 48 hours. For the first 24 hours the system was untreated and for the last 24 hours the system was treated. Test #2 was a control and tested the change in calcium carbonate particle size when treatment was not present. The test was run for a total of 48 hours. Test #3 was treated and tested the change in calcium carbonate particle size when treatment was present. The test was run for a total of 72 hours.

6.2.2 Particle Size Measurement

As mentioned earlier, all particles were measured with a Coulter N4. The measurement of particles occurred on a daily basis and began immediately after particles were added. Measurement occurred within 10 minutes after the particles and fluid were extracted from the sump.

Typically, the Coulter N4 type instruments are used to measure particle sizes in samples containing a very narrow particle size bandwidth. As can be seen from the data collected, the calcium carbonate particle samples measured with the Coulter N4 during the present investigation tended to have a large range of sizes. For this reason the data obtained with the Coulter N4 should be viewed accordingly.

6.2.3 Cleaning the System

After each test was completed the system was flushed and filled with water. Once the sump was filled with clean water the pump was turned on and the water was
allowed to circulate for an hour. The water was then flushed and the process was repeated once again. The system was then determined to be clean.

6.3 Results

For each experiment a series of particle size measurements were completed. The particle sizes were then recorded and averaged for each day. The raw tabulated data can be seen in Appendix B.

As mentioned earlier the first test, test #1 was run for 48 hours and utilized larger reagent grade calcium carbonate particles. The test was run for 24 hours without treatment and then another 24 hours with treatment. The data for each day was tabulated and averaged. The results can be seen in Table 6-1.

<table>
<thead>
<tr>
<th>Date</th>
<th>Average Size (nm)</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/11/2002</td>
<td>2465</td>
<td>Untreated</td>
</tr>
<tr>
<td>3/12/2002</td>
<td>2680</td>
<td>Untreated 24 hours</td>
</tr>
<tr>
<td>3/13/2002</td>
<td>2040</td>
<td>Treated 24 hours</td>
</tr>
</tbody>
</table>

As seen, the particle size appeared to decrease once the electrostatic water treatment was applied.

Test #2 was run for 48 hours and utilized the calcium carbonate that was obtained from Specialty Minerals. As mentioned test #2 was run without electrostatic water treatment. The data for each day was tabulated and averaged. The results can be seen in Table 6-2.
As seen, the average particle size appeared to increase as time progressed. The increase in particle size can be expected of calcium carbonate particles in suspension.

Test #3 was run for 72 hours and utilized the calcium carbonate that was obtained from Specialty Minerals. As mentioned test #3 was run with electrostatic water treatment. The data for each day was tabulated and averaged. The results can be seen in Table 6-3.

Table 6-3 Calcium carbonate particle size for treated test #3

<table>
<thead>
<tr>
<th>Date</th>
<th>Average Size (nm)</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/23/2002</td>
<td>853</td>
<td>Time 0</td>
</tr>
<tr>
<td>4/24/2002</td>
<td>932</td>
<td>Treated 24 hours</td>
</tr>
<tr>
<td>4/25/2002</td>
<td>857</td>
<td>Treated 48 hours</td>
</tr>
<tr>
<td>4/26/2002</td>
<td>931</td>
<td>Treated 72 hours</td>
</tr>
</tbody>
</table>

As seen, the average particle size appeared to maintain a relatively constant particle size.
6.4 Conclusions on the Effects of Electrostatic Water Treatment on Calcium Carbonate Particle Size

Preliminary conclusions can be made on the effectiveness of electrostatic water treatment on calcium carbonate particle size. As can be seen from Figures 6-3, 6-4 and 6-5, it appears that electrostatic water treatment does prevent the agglomeration of calcium carbonate particles. It is suggested that further testing should be completed so that these results can be validated. In addition, it is suggested variables such as temperature, pH and calcium should be monitored and recorded. As can be seen in Appendix B, some of the data varies considerably. For example, on 4/18/02 sample #2 was run twice and yielded a particle size values of 1570 nm and 1020 nm. Sample #3 was taken at the same time as sample #2 but had values of 682 nm and 651 nm. As can be seen, the particle size values varied considerably. Enhancements in particle size measurement equipment in the future will enable more definitive studied in this area.
CHAPTER 7: Experimental Studies on the Effects of Electrostatic Water Treatment on Bacterial Growth

This chapter reviews the experiments that were completed on the effects of electrostatic water treatment on bacterial growth. The effects were studied with two separate experimental setups. The first experiment setup was developed using a re-circulating pump and a large water sump. The goal of the first experiment was to simulate an industrial system and study the effects of electrostatic water treatment on planktonic bacteria in these open conditions. The second experiment was on a much smaller scale and did not re-circulate. The goal of the second experiment was to study the direct effects of electrostatic water treatment in a closed system on one particular type of planktonic bacteria. Experiments were completed with and without electrostatic water treatment applied. This would allow for the comparison and validation of the effectiveness of electrostatic water treatment on bacterial levels.

7.1 Description of the Test Apparatuses

As mentioned, two test apparatuses were built. The first was built to study the effects of electrostatic water treatment on planktonic bacteria in a re-circulating system designed to simulate an industrial system. The first test loop used water from a local stream. Since the system was built to simulate an industrial system, the water was allowed to breath the outside air. Tests were conducted with treatment and without treatment and total bacterial plate count along with coliform bacteria levels were measured. The system designed can be seen in Figure 7-1.
The second apparatus was built to study the effects of electrostatic water treatment on planktonic bacteria in a closed, controlled environment. In this test, nutrient broth was placed inside of a sealed cylindrical electrostatic water treatment device. The bacteria used, pseudomonas aeruginosa, was added and allowed to grow in the chamber. Pseudomonas aeruginosa is a planktonic, aerobic bacteria. Tests were conducted with treatment and without treatment and the plate count of the bacteria was measured. The system can be seen in Figure 7-2

Figure 7-1 First test apparatus built at Lehigh University to measure the effects of electrostatic water treatment on the effects of bacteria in simulated industrial environment
Figure 7-2 Second test apparatus built at Lehigh University to measure the effects of electrostatic water treatment on the effects of bacteria in a controlled environment

7.1.1 Components of Simulated Industrial Test Apparatus

As seen from Figure 7-1, the test apparatus consisted of four main components. These components were the water pump, water sump, voltage supply and electrostatic water treatment device. Water flowed from the sump, through the bottom of the electrostatic water treatment device and back into the sump. The sump was designed to contain 60 liters of water. A lid was placed on top of the sump. The lid prevented objects from entering the sump but still allowed the system to breath. Water flowed through PVC pipes with an inner diameter of $\frac{3}{4"}$. The pump used was a shaft driven centrifugal pump that was capable of delivering 28 liters/minute.

The electrostatic water treatment device used was a side stream style with an aluminum electrode radius of 0.0175 m. The electrode was coated with a dielectric material with a dielectric constant of 7 and a conductivity of $5 \times 10^{-13} \, \text{S/m}$ and a radius of 0.0215 m. The total electrostatic rod length was 0.63 m. The reaction
chamber was made of stainless steel with a radius of 0.0556 m. The electrostatic water treatment device was powered with a Bertan series 230 voltage supply that was capable of providing a pure D.C. voltage up to 30,000 volts at a current level up to 0.2 mA.

7.1.2 Components of the Controlled Test Apparatus

As seen from Figure 7-2, the test apparatus consisted of three main components. These include the magnetic stirrer, voltage supply and the electrostatic water treatment device. Water mixed with nutrient broth and bacteria was contained in the reaction chamber. The reaction chamber consisted of the same geometry as the device used in the simulated industrial experiment but had a smaller height of 0.356 m. This small chamber could hold 2.75 liters of water. The chamber had a small ¼” diameter hole in the top used to extract samples. When not used the hole was sealed with a rubber stopper and the chamber was completely sealed from outside contaminants. The electrostatic water treatment device was powered with the same Bertan voltage supply that was used throughout the study.

The reaction chamber was placed over a magnetic stirrer. In conjunction with the stirrer, a coated magnet was placed in the reaction chamber and effectively agitated the bacteria and fluid inside.

A second chamber was used with similar geometry and volume in order to run a control test. The control test did not utilize electrostatic water treatment.
7.2 Test Method

The two types of tests required two separate test methods. The industrial test required very little preparation and bacteria level measurements were outsourced to ABE laboratories where total plate count and coliform levels were measured. The controlled system required more preparation and the bacterial levels were measured in house. Each process will be described in detail.

7.2.1 Preparation and Testing Methods for the Industrial Test System

When testing the effects of electrostatic water treatment on bacteria, the sump was filled with 60 liters of water from a local stream in Bethlehem, Pennsylvania. The pump was turned on and the water was allowed to flow through the pipes at 28 liters/minute. The electrostatic rod was immediately turned on and supplied with 25,000 Volts DC.

This system was also used for a control experiment. It was felt that control experiments should be run so that comparisons could be made between water that was treated and untreated. In the control experiment the sump was filled again with 60 liters of water from the local stream. The pump was turned on and the water was allowed to flow through the pipes at 28 liters/min. For the control experiment, the electrostatic rod was not turned on.

Samples of water were taken from the sump on a daily basis. The samples were then delivered to ABE Laboratory in Bath, Pennsylvania within 15 minutes, where coliform, total plate count (TPC) and pH were measured and recorded. Temperatures were maintained between 20 °C and 22 °C.
7.2.2 Preparation and Testing Methods for the Controlled Test System

The preparation and testing of the bacteria in the controlled test system was more complex and time consuming. All bacteria counts were prepared and measured in house. The controlled test was designed to study the direct effects of electrostatic water treatment on pseudomonas aeruginosa. For this reason all components needed to be completely cleaned and sterilized before the beginning of each test. This would allow for only pseudomonas aeruginosa to cultivate in the reaction chamber and would eliminate the chance of competing bacteria to form. The procedure had to be followed very carefully in order to avoid contamination. During the experiment the chamber was maintained at a temperature between 20 °C and 22 °C.

7.2.2.1 Preparation of the Nutrient Broth

The procedure began with the preparation of the nutrient broth used to feed the bacteria. Three separate flasks were filled, each with a liter of distilled water. Each flask was then prepared with 8.00 grams of BASTO Nutrient Broth and agitated with a magnetic stirrer. After the nutrient broth was completely dissolved, the flask was then autoclaved for 30 minutes at a temperature of 120°C. It was imperative that the top of each flask was covered with aluminum foil to prevent contaminants from entering. Once the autoclaving was completed the broth mixture was stirred again to make sure it was homogenous.
7.2.2.2 Preparation of the Agar

An agar solution was created so that bacteria could be cultured and counted. In order to do this, two separate flasks are filled each with a liter of distilled water. Each flask was prepared with 8.00 grams of BASTO Nutrient Agar and agitated with a magnetic stirrer. After the agar was completely dissolved, the flask was then autoclaved for 30 minutes at a temperature of 120°C. Once again, it was imperative that the top of each flask was covered with aluminum foil to prevent contaminants from entering. Once the autoclaving was completed the agar mixture was stirred again to make sure it was homogenous. Then, 80 sterile petri dishes were filled with 25 ml of agar. After each plate was filled the petri dish cover had to be place on immediately. During this process it was also very important that a bunsen burner was lit near the work area. This terminated any air-born contaminates and prevented contamination of the agar plates. The agar was allowed to cool and solidify.

7.2.2.3 Preparation of the Test Cell

The test cell needed was also autoclaved for sterilization. The chamber was dismantled so that the cables were disconnected and the electrostatic rod was removed from the reaction chamber. Aluminum foil was then placed around the electrostatic rod and the outer cylinder. All components were then placed in the autoclave for 10 minutes.

After the autoclave process was completed and all components have cooled to room temperature the aluminum foil could be removed from the top of the chamber and the nutrient broth could be poured into the chamber along with the magnetic
stirrer. The electrostatic rod could then be mounted in place. A bunsen burner was lit near the working area during this process for sanitation purposes.

7.2.2.4 Preparation of Dilution Test Tubes

The dilution test tubes were used to dilute the samples of bacteria extracted from the test chamber. The test tubes were cleaned at the beginning of the experiment. If they were dirty, they needed to be put in the washing machine and then autoclaved. Next, 9.0 ml of distilled water was poured into each test tube and covered with a plastic top. Each test tube was carefully placed in a rack and then placed into the autoclave for 30 minutes at 120°C. Since 80 petri dishes were prepared about 80 test tubes with 9.0 ml of water were prepared.

7.2.2.5 Collection of Bacteria

Bacteria must be collected from a source and introduced to the reaction chamber. Once again pseudomonas aeruginosa was used in this experiment. Firstly, a bunsen burner was started and a scraper was heated for sanitation purposes. Once the scraper was cooled it was used to extract bacteria from a source petri dish. The bacteria was then inserted into 9 ml of sterilized water and stirred. One ml of water was then extracted from the test tube and introduced into the reaction chamber.

7.2.2.6 Starting the Test

Once the contents of the broth and the bacteria were placed into the reaction chamber the test could begin. The chamber was sealed and placed on top of the magnetic stirrer. The magnetic stirrer was turned on and the power supply was set to
25,000 volts and turned on. The control test followed the same procedures except that the power supply was left off.

### 7.2.2.7 Collection of Data

After 24 hours a sample of 1 ml was taken from the reaction chamber and placed in a prepared sterilized test tube with 9 ml of distilled, sterilized water. This created a dilution of 1:10. The test tube was then placed on a vortex to equally distribute the bacteria. 1mL of water was then taken from that test tube and placed in another 9mL test tube and the process continued until there were up to six test tubes. Each test tube represented a further dilution of the amount of bacteria per ml of liquid. 1mL was then taken from each test tube and placed on its own petri dish. This process can be seen in Figure 7-3.

![Diagram of dilution process](image)

**Figure 7-3 The Dilution Process for Preparing Plates Counts**
A spreader was then dipped in alcohol and placed in a flame from a Bunsen burner to sanitize and allowed to cool. The petri dish with the 1mL was placed on spinner and spun around while a spreader went back in forth to distribute the bacteria. The process was repeated for each petri dish prepared. Each plate was individually labeled for their specific test date and dilution level. After all plates completed this process, they were taped together, and dated. The petri dishes were then placed in an incubator at 37°C for 24 hours. The plates were then removed and a standard plate count was performed on the plate that had a bacteria range of 30-300 colonies through visual inspection. Each bacteria colony counted represented one bacteria count. As mentioned, the count was made on a plate that had between 30 and 300 colonies and then was multiplied by the dilution of the plate. This gave a count of the total bacteria density for 1 ml of original solution extracted from the reaction chamber.

7.2.3 Cleaning of the Experimental Systems

Both systems were thoroughly cleaned after each experiment was completed. The industrial experiment was emptied and filled with Bethlehem tap water twice. Each time the water was flushed through the system and then drained. After this was completed the system was ready for another experiment.

The controlled experiment was drained and flushed with Bethlehem tap water twice. All components were then autoclaved and sterilized. After all components were sterilized the experiment was ready for another experiment.
7.3 Results

Numerous tests were completed on the effects of electrostatic water treatment on bacteria levels. Both the simulated industrial case and the controlled case will be reviewed with and without treatment. The raw tabulated data can be seen in Appendix C.

7.3.1 Comparison Between Treated and Untreated Bacteria Levels in Simulated Industrial Test System

The first test was run with electrostatic water treatment. As mentioned, coliform, TPC and pH were measured on a daily basis. Coliform was measured after the first day of treatment. Total plate count and pH were measured during the first day of treatment. The experiment lasted for a total of 10 days. The coliform count and pH for treated water can be seen in Figure 7-4. Coliform levels were measured in terms of colony forming units (CFU per 100 ml).

The next test completed was the control. The control or untreated system was run in the same fashion as the treated system. Once again, coliform was measured after the first day of treatment. Total plate count and pH were measured during the first day of treatment. The experiment lasted for 10 days. The coliform count and pH for untreated water can be seen in Figure 7-5.
Figure 7-4 Coliform CFU per 100 ml of water and pH levels for a treated simulated industrial system.

Figure 7-5 Coliform CFU per 100 ml of water and pH levels for an untreated simulated industrial system.
As seen from these two figures, the bacteria levels both tended to follow the same life/death cycle. In addition, the pH of the systems for both experiments followed the same path. For further insight, the comparison between the treated and untreated coliform counts can be seen in Figure 7-6.

![Graph showing coliform CFU per ml of water for treated and untreated systems.](image)

**Figure 7-6** Coliform CFU 100 per ml of water for a treated and untreated simulated industrial system.

As seen from Figure 7-6, the treated coliform levels were on average higher than the untreated system. Each test seemed to follow a normal bacteria life and death cycle.

We can compare the levels of total plate count for the treated and untreated system in Figure 7-7. As seen the TPC levels were erratic and did not follow any specific cycle. The treated and untreated systems did however follow the same general path.
Lastly we can compare the pH levels for the treated and untreated experiments in Figure 7-8. As seen, the pH's in the two experiments followed the same trend and were roughly the same.

From the results of these experiments, no obvious and dramatic direct effect of the current pure D.C. electric field exposure on system planktonic bacteria levels can be seen.
7.3.2 Comparison Between Treated and Untreated Bacteria Levels in Simulated Industrial Test System

The controlled bacteria test was run with treated and untreated conditions. The treated and untreated tests were run simultaneously for nine days. For each test the total pseudomonas aeruginosa count per ml of water was measured and compared. Unfortunately it was determined from the data collected that the untreated system was contaminated and the data was discarded. Although, the treated bacteria levels can still be seen in Figure 7-9.

Figure 7-8 pH for a treated and untreated simulated industrial system.
Figure 7-9 Colony forming units per ml of water for the treated controlled test

As seen from Figure 7-9 the bacteria level followed a normal life and death cycle. It appeared that electrostatic water treatment as applied during the study did not have an effect on the growth of pseudomonas aeruginosa but no definitive conclusions could be made since a control did not exist.

7.4 Conclusions on the Effects of Electrostatic Water Treatment on the Simulated Industrial Test and the Controlled Test

Conclusions could be made on the effectiveness of electrostatic water treatment on a simulated industrial test for the specific types of bacteria tested, pH levels and temperatures used. Unfortunately, the controlled experiment was not as successful and definitive conclusions could not be made due to the lack of a control.
The coliform levels for the treated and untreated, simulated industrial tests were averaged and compared. The coliform levels in the untreated system on average were 107.41% lower than the treated system. These values can be seen in Table 7-1.

Table 7-1 Comparison of average coliform count and pH for treated and untreated conditions

<table>
<thead>
<tr>
<th></th>
<th>Coliform</th>
<th></th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treated</td>
<td>1092.2</td>
<td>Untreated</td>
<td>526.6</td>
</tr>
<tr>
<td>% Difference</td>
<td>107.41</td>
<td>% Difference</td>
<td>1.28</td>
</tr>
</tbody>
</table>

The total plate count levels were also averaged and compared for the treated and untreated systems. The TPC levels for the untreated system on average were 21.44% lower than the treated system. These values can be seen in Table 7-2.

Table 7-2 Comparison of average TPC count and pH for treated and untreated conditions

<table>
<thead>
<tr>
<th></th>
<th>TPC</th>
<th></th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treated</td>
<td>676.9</td>
<td>Untreated</td>
<td>557.4</td>
</tr>
<tr>
<td>% Difference</td>
<td>-21.44</td>
<td>% Difference</td>
<td>1.28</td>
</tr>
</tbody>
</table>

As seen from both Tables, the values of pH can be compared to the values of coliform and TPC. On average the level of pH for the untreated system was 1.28% higher than the treated system.

It can be concluded with some confidence that electrostatic water treatment as applied was not effective on reducing the levels coliform and TPC under the
conditions of pH, flow rate and temperatures studied. The experiment should be repeated two more times to make definitive conclusions.

The control test was run but was not as conclusive as the simulated industrial test. It can be seen from Figure 7-9 that the levels of bacteria follow a normal growth and death cycle. One may be tempted to conclude that the level of $1.08 \times 10^8$ colony forming units per ml would not be reached if electrostatic treatment was effective against pseudomonas aeruginosa. This should not be concluded and a control test must me tested and repeated before any definitive conclusions can be made.
CHAPTER 8: Conclusions and Recommendations

8.1 Conclusions

Electrostatic water treatment is a relatively new type of water treatment that has been introduced to industries that utilize large amounts of water where calcium carbonate, foulants and bacteria introduce major problems for thermal efficiencies, electrical efficiencies and health hazards. Currently chemicals are added to water to control the levels of calcium carbonate deposits and bacterial levels. Since chemicals need to be continually added and are sometimes hazardous to the environment an alternative method of treatment would be desirable. Electrostatic water treatment could fill this void. Very little research has been completed on electrostatic water treatment and the benefits of this needed research to industry are very apparent. Electrostatic water treatment, if proven to be a viable type of water treatment could cut costs considerably and could provide a much more environmentally friendly approach to water treatment. Proving that certain forms of electrostatic water treatment are ineffective can also be beneficial to industry as it will prevent further development and use of products that do not work.

Three major experiments were completed in order to gain more insight into effectiveness of electrostatic water treatment. The first experiment studied the effects of electrostatic water treatment on calcium carbonate deposits. The second experiment studied the effects of electrostatic water treatment on calcium carbonate
particle size. The last experiment studied the effects of electrostatic water treatment on bacteria growth. Each experiment was completed with varying levels of success.

This chapter will review the conclusions made in each experiment and will make some recommendations for further testing. The experiments completed are most certainly not complete and it is necessary to continue testing in order determine the effectiveness of electrostatic water treatment. These experiments do however provide a very useful tool to continue more useful and in depth research into the field of electrostatic water treatment.

As mentioned, the first set of tests studied the effects of electrostatic water treatment on calcium carbonate deposition. The study was run for crystallization fouling and particulate fouling. The results of the treated tests were compared to the results of the untreated tests. It was found that electrostatic water treatment as applied with a pure D.C. voltage had little to no effect on crystallization and particulate calcium carbonate deposition under the conditions of temperature, water flow rates and chemistries used. Further testing is needed to validate these claims and to study the effects of other variables. Recommendations for these experiments will be made in the next section.

The second experiment tested the effects of pure D.C. electrostatic water treatment on calcium carbonate particle size. The study was run for two sizes of particles. The test utilized larger calcium carbonate particles and was run without treatment and then with treatment. It was found that the particle size increased without treatment and then proceeded to decrease with treatment. The last two tests
were run with smaller particles. The first of the two was run without treatment and
the second was run with treatment. When comparing these two tests it was found that
the calcium carbonate particle size grew in the case without treatment and the
particles size maintained a relatively constant size with treatment. These results
prove to shed some light on the mechanism by which electrostatic water treatment
may work. Once again, these experiments should be run again in order to validate the
results. Recommendations for future testing will be made in the next section.

Lastly, experiments were also completed on the effects of electrostatic water
treatment on bacterial levels. The first experiment studied the bacteria levels in a
simulated industrial setting, the second experiment studied bacteria in a more
controlled setting. After comparing the bacteria levels for the treated test and the
untreated test in the simulated industrial setting it was determined that electrostatic
water treatment as applied during the present study had little to no direct effect on the
levels of total plate count and coliform bacteria. The controlled experiment utilized
planktonic pseudomonas aeruginosa. Unfortunately the treated and untreated
experiments could not be compared since the untreated test was invalidated due to the
introduction of contaminates. However, it was found that the bacteria in the treated
test did follow a typical life and death cycle. This may suggest that electrostatic
water treatment as applied with a pure D.C. voltage source had no effect on the
pseudomonas aeruginosa, but it is uncertain. Repeated testing is required in order to
obtain more conclusive results. Suggestion for future testing will be made in the next
section.
8.2 Recommendations

The experiments completed at Lehigh University have given some insight into understanding the effectiveness of electrostatic water treatment. Although, it has been determined that further research must be completed in order to validate or invalidate the treatment. Some suggestions and recommendations will be given for further experimentation in this section.

The first recommendation would be to run the scale deposit experiments using a different voltage supply box. It has been determined that the DC voltage supply boxes used in industry are not filtered as well as the Bertan DC voltage supply box used in the experimentation. As a result, the voltage supply boxes in industry leak a small amount of AC voltage, which is subsequently supplied to the electrostatic rod. This AC voltage as a result increases the electric field distributed through the water. If the effectiveness of electrostatic water treatment can be attributed to the strength of the electric field then the electrostatic rods in industry will operate more effectively. As a result the continued experiments should be run with the DC voltage supply boxes that are used in industry.

The next recommendation also pertains to the scale deposit experiment. It has been determined that more experimentation should be completed on scale deposition with multiple water velocities. The velocities used in the experimentation at Lehigh University do not perfectly match the velocities as seen in industry. Therefore, the conclusions made on the experiments completed cannot be applied with full confidence to an industrial situation unless the velocities are matched. More
experimentation should also be completed using multiple temperature differential and chemistry levels.

The experiments completed have shown that electrostatic water treatment may have an effect on calcium carbonate particle size. If proven, this would provide insight to the mechanism by electrostatic water treatment operates. It is recommended that a different particle size measurement instrument should be used if further testing is to commence. The Coulter N4 is a reliable machine if it is used within its capabilities. Typically, the particles that the Coulter N4 measures have a much narrower size range. The calcium carbonate particles used sometimes varied by as much as 1000 nm. This may be too large for the Coulter N4. In addition to using a new instrument, it has also been determined that the pH, calcium hardness and temperature should be monitored more closely if testing is to continue. The particle size test should also be run with the industrial voltage supply box.

Recommendations can also be made for the bacterial experiments. Since the control for the controlled bacterial experiment was contaminated it is recommended that the experiment be repeated. It is also suggested that the controlled bacterial experiment should be modified. Since pseudomonas aeruginosa is an aerobic bacteria it needs to be supplied with oxygen in order to sustain life. The chamber in which the bacteria were tested was a closed container and did not allow oxygen to enter. If experiments are to continue on the controlled pseudomonas aeruginosa oxygen should be supplied. In addition, multiple experiments should be completed so that the effects of electrostatic water treatment on bacteria can be verified.
The concept of electrostatic water treatment holds promise for widespread application in the future. Since the electrochemical phenomena involved in such treatment are complex, however, research such as that performed during the present study is needed to identify exactly when and how successful applications can be realized. While the present study has by no means closed the book in this area, it most certainly serves a very informative and important chapter.
REFERENCES


APPENDIX A

EXPERIMENTAL DATA FOR CALCIUM CARBONATE SCALE GROWTH AND REMOVAL EXPERIMENT
<table>
<thead>
<tr>
<th>Date</th>
<th>Test 1 No Treatment</th>
<th>Test 2 Treatment</th>
<th>Test 3 Treatment</th>
<th>Test 4 No Treatment</th>
<th>Test 5 No Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2/15/2002</td>
<td></td>
<td></td>
<td></td>
<td>5/7/2002 (8:40 AM)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5/7/2002 (9:40 AM)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5/7/2002 (10:40 AM)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5/8/2002</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5/9/2002</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5/10/2002</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5/11/2002</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Date</th>
<th>Test 1 No Treatment</th>
<th>Test 2 Treatment</th>
<th>Test 3 Treatment</th>
<th>Test 4 No Treatment</th>
<th>Test 5 No Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2/15/2002</td>
<td></td>
<td></td>
<td></td>
<td>5/7/2002 (8:40 AM)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5/7/2002 (9:40 AM)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5/7/2002 (10:40 AM)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5/8/2002</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5/9/2002</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5/10/2002</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5/11/2002</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Date</th>
<th>Test 1 No Treatment</th>
<th>Test 2 Treatment</th>
<th>Test 3 Treatment</th>
<th>Test 4 No Treatment</th>
<th>Test 5 No Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2/15/2002</td>
<td></td>
<td></td>
<td></td>
<td>5/7/2002 (8:40 AM)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5/7/2002 (9:40 AM)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5/7/2002 (10:40 AM)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5/8/2002</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5/9/2002</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5/10/2002</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5/11/2002</td>
</tr>
<tr>
<td>Date</td>
<td>Treatment</td>
<td>CaCl</td>
<td>MgSO</td>
<td>NaH</td>
<td>Na2</td>
</tr>
<tr>
<td>------------</td>
<td>-----------------</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>Test 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/13/2002</td>
<td>(9:00 PM)</td>
<td>63.0</td>
<td>142.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/13/2002</td>
<td>(9:20 PM)</td>
<td>20.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/13/2002</td>
<td>(9:40 PM)</td>
<td>5.75</td>
<td>1.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/13/2002</td>
<td>(10:40 PM)</td>
<td>5.75</td>
<td>1.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/13/2002</td>
<td>(11:40 PM)</td>
<td>5.75</td>
<td>1.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/13/2002</td>
<td>(12:40 PM)</td>
<td>5.75</td>
<td>1.25</td>
<td>1100</td>
<td>450</td>
</tr>
<tr>
<td>5/14/2002</td>
<td></td>
<td>1110</td>
<td>480</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/15/2002</td>
<td></td>
<td>1100</td>
<td>450</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/16/2002</td>
<td></td>
<td>1100</td>
<td>440</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/17/2002</td>
<td></td>
<td>1070</td>
<td>445</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test 7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/21/2002</td>
<td>(8:00 AM)</td>
<td>63.0</td>
<td>142.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/21/2002</td>
<td>(8:20 AM)</td>
<td>40.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/21/2002</td>
<td>(9:00 AM)</td>
<td>11.5</td>
<td>2.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/21/2002</td>
<td>(10:00 AM)</td>
<td>11.5</td>
<td>2.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/21/2002</td>
<td>(11:00 AM)</td>
<td>11.5</td>
<td>2.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/21/2002</td>
<td>(12:00 PM)</td>
<td>11.5</td>
<td>2.50</td>
<td>1050</td>
<td>440</td>
</tr>
<tr>
<td>5/22/2002</td>
<td>(12:00 PM)</td>
<td>780</td>
<td>230</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/22/2002</td>
<td>(11:59 PM)</td>
<td>790</td>
<td>230</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test 8 No</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/30/2002</td>
<td>(8:00 PM)</td>
<td>63.0</td>
<td>142.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/30/2002</td>
<td>(8:20 PM)</td>
<td>40.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/30/2002</td>
<td>(9:00 PM)</td>
<td>11.5</td>
<td>2.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/30/2002</td>
<td>(10:00 PM)</td>
<td>11.5</td>
<td>2.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/30/2002</td>
<td>(11:00 PM)</td>
<td>11.5</td>
<td>2.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/30/2002</td>
<td>(12:00 AM)</td>
<td>11.5</td>
<td>2.50</td>
<td>1060</td>
<td>440</td>
</tr>
<tr>
<td>5/31/2002</td>
<td>(12:00 AM)</td>
<td>810</td>
<td>235</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/31/2002</td>
<td>(11:59 AM)</td>
<td>780</td>
<td>225</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Date</td>
<td>CaCl</td>
<td>MgSO</td>
<td>NaH</td>
<td>Na2</td>
<td>Total Ca</td>
</tr>
<tr>
<td>------------</td>
<td>-------</td>
<td>------</td>
<td>-----</td>
<td>------</td>
<td>----------</td>
</tr>
<tr>
<td>6/6/2002 (3:00 PM)</td>
<td>63.0</td>
<td>142.0</td>
<td>1090</td>
<td>430</td>
<td>8.2</td>
</tr>
<tr>
<td>6/6/2002 (3:20 PM)</td>
<td>20.00</td>
<td>1070</td>
<td>425</td>
<td></td>
<td>106</td>
</tr>
<tr>
<td>6/6/2002 (4:00 PM)</td>
<td>5.75</td>
<td>1.25</td>
<td>1060</td>
<td>430</td>
<td>154</td>
</tr>
<tr>
<td>6/6/2002 (5:00 PM)</td>
<td>5.75</td>
<td>1.25</td>
<td>1050</td>
<td>430</td>
<td>198</td>
</tr>
<tr>
<td>6/6/2002 (6:00 PM)</td>
<td>5.75</td>
<td>1.25</td>
<td>1070</td>
<td>425</td>
<td>238</td>
</tr>
<tr>
<td>6/6/2002 (7:00 PM)</td>
<td>5.75</td>
<td>1.25</td>
<td>1090</td>
<td>435</td>
<td>382.5</td>
</tr>
<tr>
<td>6/7/2002</td>
<td>1090</td>
<td>440</td>
<td>385</td>
<td>264</td>
<td>8.7</td>
</tr>
<tr>
<td>6/8/2002</td>
<td>1070</td>
<td>435</td>
<td>382.5</td>
<td>262</td>
<td>8.7</td>
</tr>
<tr>
<td>6/9/2002</td>
<td>1080</td>
<td>430</td>
<td>377.5</td>
<td>258</td>
<td>8.7</td>
</tr>
<tr>
<td>6/10/2002</td>
<td>1080</td>
<td>425</td>
<td>380</td>
<td>259</td>
<td>8.7</td>
</tr>
</tbody>
</table>
APPENDIX B

EXPERIMENTAL DATA FOR PARTICLE SIZE EXPERIMENT
<table>
<thead>
<tr>
<th>Date</th>
<th>Sample #</th>
<th>Run #</th>
<th>Average Size (nm)</th>
<th>Average</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/11/2002</td>
<td>1</td>
<td>1</td>
<td>2780</td>
<td></td>
<td>Time 0</td>
</tr>
<tr>
<td>3/11/2002</td>
<td>1</td>
<td>2</td>
<td>2150</td>
<td></td>
<td>Time 0</td>
</tr>
<tr>
<td>3/11/2002</td>
<td>2</td>
<td>1</td>
<td>2510</td>
<td></td>
<td>Time 0</td>
</tr>
<tr>
<td>3/11/2002</td>
<td>2</td>
<td>2</td>
<td>2420</td>
<td>2465</td>
<td>Time 0</td>
</tr>
<tr>
<td>3/12/2002</td>
<td>1</td>
<td>1</td>
<td>2710</td>
<td></td>
<td>Untreated 24 hrs.</td>
</tr>
<tr>
<td>3/12/2002</td>
<td>1</td>
<td>2</td>
<td>2700</td>
<td></td>
<td>Untreated 24 hrs.</td>
</tr>
<tr>
<td>1/211900</td>
<td>2</td>
<td>1</td>
<td>2860</td>
<td></td>
<td>Untreated 24 hrs.</td>
</tr>
<tr>
<td>3/12/2002</td>
<td>2</td>
<td>2</td>
<td>2450</td>
<td>2680</td>
<td>Untreated 24 hrs.</td>
</tr>
<tr>
<td>3/13/2002</td>
<td>1</td>
<td>1</td>
<td>2130</td>
<td></td>
<td>treated 24 hrs</td>
</tr>
<tr>
<td>3/13/2002</td>
<td>1</td>
<td>2</td>
<td>1970</td>
<td></td>
<td>treated 24 hrs</td>
</tr>
<tr>
<td>3/13/2002</td>
<td>2</td>
<td>1</td>
<td>1990</td>
<td></td>
<td>treated 24 hrs</td>
</tr>
<tr>
<td>3/13/2002</td>
<td>2</td>
<td>2</td>
<td>2070</td>
<td>2040</td>
<td>treated 24 hrs</td>
</tr>
</tbody>
</table>

**Test 2**

<table>
<thead>
<tr>
<th>Date</th>
<th>Sample #</th>
<th>Run #</th>
<th>Average Size (nm)</th>
<th>Average</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/16/2002</td>
<td>1</td>
<td>1</td>
<td>832</td>
<td></td>
<td>Time 0</td>
</tr>
<tr>
<td>3/16/2002</td>
<td>2</td>
<td>1</td>
<td>774</td>
<td></td>
<td>Time 0</td>
</tr>
<tr>
<td>3/16/2002</td>
<td>3</td>
<td>1</td>
<td>562</td>
<td>723</td>
<td>Time 0</td>
</tr>
<tr>
<td>3/17/2002</td>
<td>1</td>
<td>1</td>
<td>1240</td>
<td></td>
<td>Untreated 24 hrs.</td>
</tr>
<tr>
<td>3/18/2002</td>
<td>1</td>
<td>1</td>
<td>1130</td>
<td></td>
<td>Untreated 48 hrs.</td>
</tr>
<tr>
<td>3/18/2002</td>
<td>2</td>
<td>1</td>
<td>1570</td>
<td></td>
<td>Untreated 48 hrs.</td>
</tr>
<tr>
<td>3/18/2002</td>
<td>2</td>
<td>2</td>
<td>1020</td>
<td></td>
<td>Untreated 48 hrs.</td>
</tr>
<tr>
<td>3/18/2002</td>
<td>3</td>
<td>1</td>
<td>682</td>
<td></td>
<td>Untreated 48 hrs.</td>
</tr>
<tr>
<td>3/18/2002</td>
<td>3</td>
<td>2</td>
<td>651</td>
<td></td>
<td>Untreated 48 hrs.</td>
</tr>
<tr>
<td>3/18/2002</td>
<td>4</td>
<td>1</td>
<td>1210</td>
<td>1044</td>
<td>Untreated 48 hrs.</td>
</tr>
<tr>
<td>Date</td>
<td>Sample #</td>
<td>Run #</td>
<td>Average Size (nm)</td>
<td>Average</td>
<td>Comments</td>
</tr>
<tr>
<td>------------</td>
<td>----------</td>
<td>-------</td>
<td>-------------------</td>
<td>---------</td>
<td>--------------</td>
</tr>
<tr>
<td>3/23/2002</td>
<td>1</td>
<td>1</td>
<td>740</td>
<td></td>
<td>Time 0</td>
</tr>
<tr>
<td>3/23/2002</td>
<td>2</td>
<td>1</td>
<td>990</td>
<td></td>
<td>Time 0</td>
</tr>
<tr>
<td>3/23/2002</td>
<td>2</td>
<td>2</td>
<td>811</td>
<td></td>
<td>Time 0</td>
</tr>
<tr>
<td>3/23/2002</td>
<td>2</td>
<td>3</td>
<td>968</td>
<td></td>
<td>Time 0</td>
</tr>
<tr>
<td>3/23/2002</td>
<td>3</td>
<td>1</td>
<td>755</td>
<td>853</td>
<td>Time 0</td>
</tr>
<tr>
<td>3/24/2002</td>
<td>1</td>
<td>1</td>
<td>988</td>
<td></td>
<td>Treated 24 hrs.</td>
</tr>
<tr>
<td>3/24/2002</td>
<td>1</td>
<td>2</td>
<td>916</td>
<td></td>
<td>Treated 24 hrs.</td>
</tr>
<tr>
<td>3/24/2002</td>
<td>2</td>
<td>1</td>
<td>874</td>
<td></td>
<td>Treated 24 hrs.</td>
</tr>
<tr>
<td>3/24/2002</td>
<td>3</td>
<td>1</td>
<td>946</td>
<td></td>
<td>Treated 24 hrs.</td>
</tr>
<tr>
<td>3/24/2002</td>
<td>3</td>
<td>2</td>
<td>938</td>
<td>932</td>
<td>Treated 24 hrs.</td>
</tr>
<tr>
<td>3/25/2002</td>
<td>1</td>
<td>1</td>
<td>819</td>
<td></td>
<td>Treated 48 hrs.</td>
</tr>
<tr>
<td>3/25/2002</td>
<td>1</td>
<td>2</td>
<td>630</td>
<td></td>
<td>Treated 48 hrs.</td>
</tr>
<tr>
<td>3/25/2002</td>
<td>2</td>
<td>1</td>
<td>904</td>
<td></td>
<td>Treated 48 hrs.</td>
</tr>
<tr>
<td>3/25/2002</td>
<td>2</td>
<td>2</td>
<td>825</td>
<td></td>
<td>Treated 48 hrs.</td>
</tr>
<tr>
<td>3/25/2002</td>
<td>3</td>
<td>1</td>
<td>1020</td>
<td></td>
<td>Treated 48 hrs.</td>
</tr>
<tr>
<td>3/25/2002</td>
<td>3</td>
<td>2</td>
<td>1010</td>
<td></td>
<td>Treated 48 hrs.</td>
</tr>
<tr>
<td>3/25/2002</td>
<td>4</td>
<td>1</td>
<td>855</td>
<td></td>
<td>Treated 48 hrs.</td>
</tr>
<tr>
<td>3/26/2002</td>
<td>1</td>
<td>1</td>
<td>909</td>
<td></td>
<td>Treated 72 hrs.</td>
</tr>
<tr>
<td>3/26/2002</td>
<td>1</td>
<td>2</td>
<td>919</td>
<td></td>
<td>Treated 72 hrs.</td>
</tr>
<tr>
<td>3/26/2002</td>
<td>1</td>
<td>3</td>
<td>966</td>
<td>931</td>
<td>Treated 72 hrs.</td>
</tr>
</tbody>
</table>
APPENDIX C

EXPERIMENTAL DATA FOR BACTERIA EXPERIMENT
### Coliform and Total Plate Count Tests

<table>
<thead>
<tr>
<th>Date</th>
<th>Un-Treated</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coliform</td>
<td>TPC</td>
<td>pH</td>
<td></td>
</tr>
<tr>
<td>20-Sep</td>
<td>360</td>
<td>340</td>
<td>360</td>
<td>340</td>
</tr>
<tr>
<td>21-Sep</td>
<td>390</td>
<td>90</td>
<td>390</td>
<td>90</td>
</tr>
<tr>
<td>24-Sep</td>
<td>1000</td>
<td>220</td>
<td>1000</td>
<td>220</td>
</tr>
<tr>
<td>25-Sep</td>
<td>1050</td>
<td>190</td>
<td>1050</td>
<td>190</td>
</tr>
<tr>
<td>26-Sep</td>
<td>760</td>
<td>1400</td>
<td>760</td>
<td>1400</td>
</tr>
<tr>
<td>27-Sep</td>
<td>560</td>
<td>259</td>
<td>560</td>
<td>259</td>
</tr>
<tr>
<td>28-Sep</td>
<td>520</td>
<td>405</td>
<td>520</td>
<td>405</td>
</tr>
<tr>
<td>1-Oct</td>
<td>280</td>
<td>1100</td>
<td>280</td>
<td>1100</td>
</tr>
<tr>
<td>2-Oct</td>
<td>80</td>
<td>150</td>
<td>80</td>
<td>150</td>
</tr>
<tr>
<td>3-Oct</td>
<td>100</td>
<td>1400</td>
<td>100</td>
<td>1400</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Date</th>
<th>Treated</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coliform</td>
<td>TPC</td>
<td>pH</td>
<td></td>
</tr>
<tr>
<td>20-Sep</td>
<td>340</td>
<td>340</td>
<td>340</td>
<td>340</td>
</tr>
<tr>
<td>21-Sep</td>
<td>320</td>
<td>94</td>
<td>320</td>
<td>94</td>
</tr>
<tr>
<td>24-Sep</td>
<td>2400</td>
<td>300</td>
<td>2400</td>
<td>300</td>
</tr>
<tr>
<td>25-Sep</td>
<td>2400</td>
<td>220</td>
<td>2400</td>
<td>220</td>
</tr>
<tr>
<td>26-Sep</td>
<td>1640</td>
<td>1400</td>
<td>1640</td>
<td>1400</td>
</tr>
<tr>
<td>27-Sep</td>
<td>1570</td>
<td>480</td>
<td>1570</td>
<td>480</td>
</tr>
<tr>
<td>28-Sep</td>
<td>560</td>
<td>355</td>
<td>560</td>
<td>355</td>
</tr>
<tr>
<td>1-Oct</td>
<td>440</td>
<td>280</td>
<td>440</td>
<td>280</td>
</tr>
<tr>
<td>2-Oct</td>
<td>340</td>
<td>1500</td>
<td>340</td>
<td>1500</td>
</tr>
<tr>
<td>3-Oct</td>
<td>160</td>
<td>1800</td>
<td>160</td>
<td>1800</td>
</tr>
</tbody>
</table>

### Pseudomonas Test

<table>
<thead>
<tr>
<th>Treated Chamber</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hours</td>
<td>Pseudomonas count</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>8000000</td>
<td></td>
</tr>
<tr>
<td>48</td>
<td>10000000</td>
<td></td>
</tr>
<tr>
<td>72</td>
<td>9700000</td>
<td></td>
</tr>
<tr>
<td>144</td>
<td>108000000</td>
<td></td>
</tr>
<tr>
<td>168</td>
<td>400000000</td>
<td></td>
</tr>
<tr>
<td>216</td>
<td>150000000</td>
<td></td>
</tr>
</tbody>
</table>
C. Alexis Bennett was born in Montreal, Canada on July 30, 1977. Very shortly thereafter he and his mother moved to the Philadelphia region. In 1996, he graduated with honors from North Penn High School in Lansdale, PA. He then continued his education at Lehigh University in Bethlehem, PA where he received his Bachelor’s of Science in Mechanical Engineering. After graduating from Lehigh University with honors in 2000 he continued at Lehigh University with a Presidential Scholarship. During that time he worked under Dr. John P. Coulter and studied electrostatic water treatment. In January of 2003 he received a Master’s of Science degree in Mechanical Engineering and Mechanics from Lehigh University in Bethlehem, Pennsylvania.
END OF TITLE