

THESIS

ANALYSIS OF BALL CORPORATION'S FAIRFIELD CAN MANUFACTURING PLANT  
AND THE POTENTIAL FOR INDUSTRIAL WASTEWATER RECYCLING

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## ABSTRACT

### ANALYSIS OF BALL CORPORATION'S FAIRFIELD CAN MANUFACTURING PLANT AND THE POTENTIAL FOR INDUSTRIAL WASTEWATER RECYCLING

Ball Corporation is an American manufacturing company based in Broomfield, CO, which is best known for its work in the aluminum can and packaging industry. Ball Corporation has a vision of becoming a more sustainable and environmentally responsible manufacturer around the globe. With this in mind, Ball Corporation approached Colorado State University in the spring of 2015 with a request to conduct a study on the feasibility of conserving water use in its manufacturing plants.

This study is the result of that initial request. Ball Corporation's can manufacturing plant in Fairfield, California was studied in three different phases. The first phase involved a water audit of the Fairfield plant. The can washers at the plant produce 80% of the plants wastewater and were quickly identified as the primary opportunity for recycling. City of Fairfield municipal water quality was characterized and set as the target water quality for the treatment and recycling process. By comparing the effluent industrial wastewater quality to the city's municipal water quality, macro parameters of most concern such as suspended solids, total organic carbon (TOC), and dissolved solids were determined. Effluent water from the plant averaged a turbidity of 23 NTUs, a conductivity of 6.46 mS/ $\mu$ m, and a TOC of 105 mg/L, while the municipal water quality reported 0.065 NTUs, 0.346 mS/ $\mu$ m, and 2 mg/L of TOC.

The second phase of the study involved the actual bench scale testing of treatment processes at CSU. From June 2015 to March 2016, ten different grab samples of industrial

wastewater from the Fairfield plant were sent to CSU. These samples were treated through coagulation, filtration, granular activated carbon, and reverse osmosis processes. The main results suggested that chemical coagulation was effective in removing some suspended solids, but not TOC. Electrocoagulation showed more promise in removing TOC. Ultrafiltration was very effective at eliminating suspended solids, but was unable to reduce TOC. TOC concentrations remained high after 0.05  $\mu\text{m}$  ultrafiltration and even after 1 kDa filtration. Granular activated carbon (GAC) was able to reduce and completely remove 100% of TOC concentration with high enough doses. This reduction of TOC, was helpful in reverse osmosis. Reduction in TOC with GAC proved to increase flux across the membranes and produce a more pure permeate. After bench testing, a full treatment train of electrocoagulation, ultrafiltration, GAC, and reverse osmosis was proposed. This treatment train produced water quality with a turbidity of 0 NTU, conductivity of 0.32  $\text{mS}/\mu\text{m}$ , and a TOC of 0  $\text{mg}/\text{L}$ . This matches the municipal water quality goal.

The third phase of the project involved a cost analysis of the proposed treatment train. WaterTectonics, a water treatment company out of Everett, WA, assisted CSU in providing pilot scale treatment options for Ball to consider. A 20 GPM treatment train consisting of electrocoagulation, ultrafiltration, GAC, and reverse osmosis was compared to an identical treatment train without the electrocoagulation step. The price difference for Ball to consider between the two pilots was \$30,000.

## TABLE OF CONTENTS

ABSTRACT.....	ii
LIST OF TABLES .....	vi
LIST OF FIGURES .....	vii
1. Introduction.....	1
2. Literature Review.....	4
2.1. Ball Corporation and Water Demand.....	4
2.2. Overview of Industrial Wastewater Treatment and Recycling Projects .....	6
2.3. Review of Treatment Technologies .....	11
2.3.1. Electrocoagulation .....	11
2.3.2. Dissolved Air Flotation.....	13
2.3.3. Ultrafiltration .....	14
2.3.4. Granular Activated Carbon.....	16
2.3.5. Reverse Osmosis.....	18
2.4. Purpose & Objectives.....	20
3. Phase I: Fairfield Water Audit.....	22
3.1. Objectives of Water Audit.....	22
3.2. Fairfield, CA – Metal Beverage Packaging Division Plant.....	22
3.3. General Water Audit of Plant.....	23
3.4. Washer Audit of Plant .....	25
3.5. Water Quality Data.....	27
3.6. Discharge Water Quality Requirements.....	30
3.7. Treatment and Recycling Goals .....	31
3.8. Proposed Process Analysis.....	32
4. Phase II: Bench Scale Testing.....	36
4.1. Coagulation .....	36
4.1.1. Chemical Coagulants – Procedures and Results.....	36
4.1.2. Electrocoagulation – Procedures and Results .....	38
4.1.3. Coagulation – Discussion of Results .....	40

4.2. Ultrafiltration.....	43
4.2.1. Small Scale Ultrafiltration – Procedures and Results .....	43
4.2.2. Large Scale Ultrafiltration – Procedures and Results .....	46
4.2.3. Ultrafiltration – Discussion of Results.....	48
4.3. Granular Activated Carbon .....	51
4.3.1. GAC – Isotherms and Small Scale Testing.....	51
4.3.2. GAC – Large Scale Testing and Results.....	54
4.3.3. GAC – Discussion of Results .....	55
4.4. Reverse Osmosis .....	58
4.4.1. Reverse Osmosis – Modeling and Small Scale Testing.....	58
4.4.2. Reverse Osmosis – Large Scale Testing.....	60
4.4.3. Reverse Osmosis – Results and Discussion.....	62
4.5. Full Treatment Train Comparison.....	66
5. Phase III: Cost Analysis.....	69
5.1. Phase III Approach.....	69
6. Conclusion and Recommendation to Ball Corporation .....	72
6.1. Conclusion and Recommendation.....	72
6.2. Opportunities for Future Work.....	72
7. References.....	74
Appendix A: Coagulation .....	76
Appendix B: Ultrafiltration.....	79
Appendix C: Granular Activated Carbon .....	82
Appendix D: Reverse Osmosis .....	85

## LIST OF TABLES

Table 2.1: Reported Studies with GAC Filter Bed as Pretreatment from Monnot.....	18
Table 3.1: Line 1 and Line 2 Specifications – 12oz Cans .....	26
Table 3.2: Line 3 Specifications – 12oz Cans.....	26
Table 3.3: Water Quality Results – From Multiple Sources and Labs .....	29
Table 3.4: Change in Water Quality, Influent to Effluent .....	29
Table 3.5: Local Contaminant Limits as Reported by City of Fairfield .....	30
Table 3.6: Suggested Treatment Processes and Testing .....	32
Table 4.1: Iron Coagulant Results – Set 1 .....	37
Table 4.2: Alum Coagulant Results – Set 1 .....	37
Table 4.3: Iron and Alum Coagulant Results – Set 2 .....	38
Table 4.4: Initial Large EC Trial – 1x Dose .....	40
Table 4.5: Iron Coagulant Progression – Set 1 .....	44
Table 4.6: Alum Coagulant Progression – Set 1 .....	44
Table 4.7: Stirred Cell Results – Set 1 .....	45
Table 4.8: After 6µm and 50kDa Ultrafiltration – Set 2.....	46
Table 4.9: Large Scale UF Unit Results .....	47
Table 4.10: GAC Optimal Dose Test – Initial Characteristics .....	52
Table 4.11: Optimal Dose Results – Alum 30 mg/L .....	53
Table 4.12: Optimal Dose Results – Iron 20 mg/L.....	53
Table 4.13: Optimal Dose Results – EC (1x) .....	53
Table 4.14: Tested Membranes and Feed Pressures .....	59
Table 4.15: Reverse Osmosis – 25 Hour Fouling Test .....	62
Table 4.16: Reverse Osmosis Fouling Trial – Ion Results .....	65
Table 4.17: Train 1 (With Electrocoagulation) – Results .....	67
Table 4.18: Train 2 (No Electrocoagulation) – Results .....	68
Table 5.1: Train 1 – WaterTectonics Cost Proposal (With EC) .....	70
Table 5.2: Train 2 – WaterTectonics Cost Proposal (Without EC) .....	71
Table A.1: Raw Water Samples.....	76

Table A.2: Alum Coagulation Results .....	77
Table A.3: Iron Coagulation Results .....	77
Table A.4: After EC and 8 $\mu$ m Filtration Results .....	77
Table A.5: After EC, 8 $\mu$ m, and 0.22 $\mu$ m Filtration Results .....	77
Table B.1: Iron Coagulation after 6 $\mu$ m Filtration .....	79
Table B.2: Iron Coagulation after 1.5 $\mu$ m Filtration .....	79
Table B.3: Iron Coagulation after 0.2 $\mu$ m Filtration .....	79
Table B.4: Alum Coagulation after 6 $\mu$ m Filtration .....	80
Table B.5: Alum Coagulation after 1.5 $\mu$ m Filtration .....	80
Table B.6: Alum Coagulation after 0.2 $\mu$ m Filtration .....	80
Table B.7: List of Dissolved Substances Tested by ALS Laboratories .....	81
Table C.1: Contact Test Results in mg/L of TOC .....	82
Table C.2: GAC Exhaustion Curve Results.....	83
Table C.3: GAC Isotherm Data – Electrocoagulation .....	84
Table C.4: GAC Isotherm Data – Iron Coagulation (20 mg/L) .....	84
Table C.5: GAC Isotherm Data – Alum Coagulation (30 mg/L) .....	84
Table D.1: WinFlows Input Data for TDS Concentrations .....	86
Table D.2: Small Scale Reverse Osmosis Trials – Electrocoagulation .....	89
Table D.3: Small Scale Reverse Osmosis Trials – Iron Coagulation (20 mg/L) .....	90
Table D.4: Table of pH Difference in Small Scale Reverse Osmosis Trials .....	91



## LIST OF FIGURES

Figure 2.1: Electrocoagulation Process – Copyright WaterTectonics .....	13
Figure 2.2: Typical DAF System from Ross .....	14
Figure 2.3: GE Hollow Fiber Membranes from GE Water .....	15
Figure 2.4: WinFlows Main Interface from GE Water.....	19
Figure 3.1: General Fairfield Plant Water Flow Schematic for Entire Plant .....	24
Figure 3.2: Fairfield Washer Water Flow Schematic – Lines/Washers 1-3 .....	27
Figure 3.3: Amicon Stirred Cell Ultrafiltration Unit .....	34
Figure 3.4: Millipore 1 kDa Filter.....	34
Figure 3.5: B-KER™ 2 Liter Mixing Jar.....	35
Figure 3.6: Jar Test Mixer.....	35
Figure 3.7: Sartorius™ Vivaflow 50 .....	35
Figure 3.8: Sterlitech™ SEPA CF Filter .....	35
Figure 4.1: EC Control Unit .....	39
Figure 4.2: EC Cell .....	39
Figure 4.3: Chemical Coagulants – pH.....	41
Figure 4.4: Electrocoagulation and Ultrafiltration – TOC Reduction .....	41
Figure 4.5: Sludge Production – Total Solids Comparison (mg/L) .....	42
Figure 4.6: Vacuum Filtration - 6µm, 1.5µm .....	44
Figure 4.7: Syringe Filter - 0.2µm .....	44
Figure 4.8: Large UF Unit and Diagram.....	47
Figure 4.9: Chemical Coagulant Turbidity Progression – Set 1, 25 mg/L Doses.....	48
Figure 4.10: Conductivity Progression - Set 1 .....	49
Figure 4.11: pH Progression - Set 1 .....	50
Figure 4.12: Optimal Contact Time Results .....	52
Figure 4.13: GAC Exhaustion Test - Small Column .....	54
Figure 4.14: 1” Diameter Column .....	54
Figure 4.15: 3” Diameter GAC Column.....	55
Figure 4.16: GAC - Dosage vs. % TOC Removal.....	56

Figure 4.17: GAC Jar Tests - pH vs. Dose .....	57
Figure 4.18: GAC Jar Tests - Conductivity vs. Dose .....	57
Figure 4.19: Reverse Osmosis – GE-AG WinFlow Results .....	59
Figure 4.20: Large Scale Reverse Osmosis – SEPA Cell .....	61
Figure 4.21: Small Scale Reverse Osmosis – TDS Comparison .....	63
Figure 4.22: Small Scale Reverse Osmosis – Permeate TOC Comparison .....	64
Figure 4.23: Small Scale Reverse Osmosis – Flux Comparison .....	64
Figure A.1: WaterTectonics Electrocoagulation Calculator Spreadsheet.....	78
Figure D.1: WinFlows Model Screen Shot – Influent Water Data Interface.....	87
Figure D.2: WinFlows Model Screen Shot – Membrane GE-AK Results .....	88
Figure D.3: WinFlows Model Screen Shot – Membrane GE-CE Results.....	88
Figure D.4: Graph of pH Difference in Small Scale Reverse Osmosis Trials.....	91

## CHAPTER 1: INTRODUCTION

Corporations and large firms have recently begun to place added importance on aspects such as sustainability, low carbon footprints, and efficient energy use. Key results from a 2009 survey of corporate energy strategies found that corporations are targeting average energy savings of 20% (Prindle, 2009). By treating electricity use as a crucial means of production that can be made more efficient, corporations are not only saving money by cutting energy requirements, but also achieving favorable public relations. Leaders in sustainability and energy use are often also leaders in their industry. This trend of efficient electricity usage will soon be reflected in the area of water demand. As readily available water becomes less accessible, its value will increase. Corporations will give more focus to integrated, efficient water use in order to become leaders in sustainable water in their respective markets.

Treating and recycling water for reuse on site rather than discharging wastewater to the public wastewater treatment plant is one way in which corporations and manufacturers can become more efficient in their water use. Understanding the advantages and disadvantages of water reuse is crucial for a business to make a sound financial decision. By treating and recycling water on site, manufacturing plants are less exposed to drought-induced water restriction laws, have direct control over influent water quality, and can cut their water use and wastewater disposal costs (National Research Council, 2012). These benefits can be especially valuable as conventional water resources become more limited and water demand increases. Onsite treatment and reuse may be expensive, but the additional benefits outweigh the costs in many dry, populous, or water restricted areas around the world (National Research Council, 2012).

One of these dry and populous areas where industrial water reuse is a viable option is northern California. The historic California drought of 2015 brought about unprecedented water restrictions that threatened the survival of many businesses dependent on large amounts of municipal water. At this same time, Colorado State University professor Dr. Ken Carlson was approached by Ball Corporation executives to perform a study on the feasibility of treating and recycling wastewater effluent from their manufacturing plants. Ball Corporation produces over 50% of the aluminum cans worldwide and uses large amounts of water in the can manufacturing process to wash the cans. Initially, the proposal by Dr. Ken Carlson and Dr. Sybil Sharvelle was intended for the can manufacturing plant in Golden, CO, as per Ball Corporation's request. However, because of the water crisis in California, the study was moved to the can manufacturing plant in Fairfield, CA. This thesis summarizes the research conducted from Ball Corporation's Fairfield manufacturing plant.

The work presented in this thesis has been done in coordination with Ball Corporation. The bulk of the research was conducted during the summer and fall of 2015 and presented to Ball Corporation as described in the initial proposal. The initial proposal divided the research into three phases: a water audit of the Fairfield plant, bench scale testing of water treatment technologies at Colorado State University's environmental engineering labs, and a cost proposal. These three phases are the main chapters of the report. Also included in this thesis is a literature review to provide context, a discussion of future work, and finally an appendix to show all raw data.

The remainder of this thesis can be broken down into the following chapters:

Chapter 2 consists of a literature review of published literature involving current water demand issues, industrial water reuse, and treatment technologies evaluated in this study. The

treatment technologies discussed in the literature review correspond to the technologies evaluated in the experimental phase of the study. Purpose and objectives of the thesis are stated at the conclusion of Chapter 2 and show how this study fits with the previous research.

Chapter 3 describes Phase I: Fairfield Water Audit. This water audit shows the initial conditions of the Fairfield can manufacturing plant including wastewater quantities and qualities. It also suggests treatment technologies that were tested in Phase II of the research.

Chapter 4 focuses on Phase II: Bench Scale Results. Water quality results obtained through bench scale modeling at CSU's environmental engineering labs show the effectiveness of many different types of processes suggested in Phase I. Each treatment technology is evaluated thoroughly and advantages and disadvantages of each are discussed.

Chapter 5 presents the brief Phase III: Cost Proposals. Pilot scale cost proposals for water recycling at the Fairfield plant are compared and a recommendation to Ball Corporation is given.

Chapter 6 discusses a final conclusion and proposes future work for the study. Other tested results and fact sheets are included in the final appendices.

## CHAPTER 2: LITERATURE REVIEW

### 2.1. Ball Corporation and Water Demand

The five Ball brothers founded Ball in 1880 and since then Ball Corporation has grown to become a company of over 14,500 employees (*About Ball*, 2016). The brothers first began by making wood-jacketed tin cans for products like paint and kerosene, but since their beginning Ball Corporation has engaged in over 45 different industries (*About Ball*, 2016). Today, Ball Corporation is best known for their aerospace and technologies program. Yet it's their aluminum can manufacturing for soda and beer companies, like Coca-Cola and Anheuser Busch InBev, which provides much of their yearly revenue. According to Ball Corporation's 2013 Overview report, global can manufacturing accounted for 74% of the company's total sales and 77% of its comparable earnings. Ball Corporation also intends to grow its can manufacturing capacity by merging with its competitor Rexam PLC. IBISWorld, a comprehensive collection of industry market research and ratings, shows that Ball Corporation already holds the highest market share in the metal can & container manufacturing industry in the US at 23.7% and looks to gain another 6.6% by acquiring Rexam. Internationally, the merger would combine the top two beverage can manufacturers with the combined company having 60% of the beverage can market in North America, 69% in Europe, and 74% in Brazil (Eagle, 2015). This rapid business growth is one of many reasons Ball Corporation is pursuing more sustainable and efficient water options in its manufacturing process.

The manufacturing of aluminum cans is a highly automated, process with multiple steps. Heavy, mostly recycled, aluminum coils are unrolled, cut, and stretched to form the cylindrical base shape for the can. The cans are then trimmed to a uniform height and washed thoroughly

for disinfection and quality. After washing, the inside of the cans are coated to protect product integrity from the acidic beverage conditions and labeled. More size adjustments are also made to the cans, and they are all checked for pinholes or other imperfections. Finally, the cans are shipped to beverage makers to be filled and capped. In all, the Ball can manufacturing process is twenty individual steps long. The washing step, step six of twenty, is by far the most water intensive step and this study's main focus.

The water use in the can manufacturing process is a crucial component in ensuring can quality and consistency. Water resources, however, face tighter restrictions, higher demands, and greater future shortages than at any other time in history. The recent California drought brought about unprecedented water restrictions including a statewide 25% reduction in potable urban water usage, strong lawn conversion incentives, and prohibition of public street median irrigation (Exec. Order No. B-29-15, 2015). Water demand also continues to grow exponentially. According to the United Nations World Water Development Report 2015, water demand is expected to increase by 55% by 2050. Water stressed areas of the world such as southwestern United States, Middle East, China, and India contain some of the fastest growing populations. And unfortunately, the solution to this problem will likely not be to simply exploit conventional water resources. The same UN World Water Report also states that 20% of the world's aquifers are already over-exploited. This includes California's Central Valley aquifer, which according to USGS data, has lost 74 billion cubic meters of water since 1960. Once water from these aquifers is used up, it could be gone forever since it often takes thousands of years for surface water to recharge aquifers.

Even with these growing water stressors, Ball Corporation rarely is unable to secure consistent, high quality tap water in the United States and other developed nations. However,

water rights issues and water reliability worries have become concerns for Ball in less developed countries. In addition, droughts in developed nations, such as the drought in California, threaten to result in water restrictions. If their manufacturing plant in Fairfield, CA, was required to cut water use by 50%, production would likely drop by 50%. For a company highly invested in an industry where the profit margins are small, any cut in water use could be devastating. Ball Corporation understands their dependence on high quality, reliable tap water and realizes the opportunity on-site water treatment and recycling could bring to their business.

Many businesses and corporations today monitor their energy efficiency and generate positive public relations through zero carbon footprint or “green” initiatives. Few companies, however, value water the same way they value energy. On-site water treatment and recycling could propel Ball Corporation as an instant leader in responsible water management. It also fits very well into Ball Corporation’s new company vision. Ball’s most recent initiative, the Drive for 10 vision, strives to balance economic, environmental, and social impacts for greater long-term success. By pursuing more advanced water solutions like treating and recycling their industrial water use, Ball Corporation leverages their know-how and technological expertise to provide a competitive advantage.

## **2.2. Overview of Industrial Wastewater Treatment and Recycling Projects**

In the Federal Water Pollution Control Act Amendments of 1972, industry was required to achieve the goal of zero discharge by 1985. This was an incredibly lofty goal, which has not nearly been satisfied today, but it set into motion the incentive for industries to reuse/recycle their wastewaters. Reclaimed or recycled water use on a volume basis is expected to grow at an estimated 15% per year in the United States with applications ranging from irrigation of golf courses to groundwater recharge (Miller 66, 2006). Today, only 7.4% of wastewater is



reclaimed and reused, which suggests enormous potential for growth in this field (Miller 66, 2006). Early applications of water reuse involved irrigation of golf courses and landscapes because these operations were more economically feasible. Beginning applications of water reuse in the United States occurred in California, Florida, and even at Grand Canyon National Park. These reuse applications all involved treating general wastewater to a basic, less expensive level and using it in ways that minimize human contact. However, as treatment technologies have improved and become less expensive, specific industrial wastestreams have become more economically feasible for advanced treatment and reuse. Water reuse becomes more practical when social benefits, local economic development, watershed benefits, and public health improvements are taken into account (Miller 68, 2006). Multiple case studies on specific industrial wastewaters and their reuse exist and are summarized in the following paragraphs. This should provide some context to the Ball reuse project and this thesis.

In Jamnagar, India, one of the world's largest oil refinery's utilizes water treatment and reuse. The refinery itself has a capacity of 1.2 million barrels per day, which contributes an average of 48,000 m<sup>3</sup>/day of wastewater to the reclamation facility (Lahnsteiner, 2005). The reclamation facility segregates wastewater into four identical wastestreams. Two streams are designed for low total dissolved solids concentration (LTDS) and are treated to an effluent quality adequate for reuse in cooling water, fire water, and irrigation. Another stream, the high total dissolved solids stream (HTDS) is composed of process and oily wastewaters and is treated to a level adequate for re-use as partial make up in a sea water cooling tower (Waterleau, 2016). The general treatment process consists of oil removal through an API-separator and dissolved air flotation, biological treatment (biotowers with plastic packings and activated sludge process), tertiary filtration (dual media filters), and polishing with granular activated carbon (Lahnsteiner,

2005). The combination of these processes results in treated waters with below 5 mg/L total suspended solids, 50 mg/L COD (chemical oxygen demand), 5 mg/L oil and grease, and a pH range of 6-8. Operating costs for this plant amount to \$0.36/m<sup>3</sup> with a third of the costs coming from capital expenses. This total cost is more economical and environmentally sustainable than the alternative: seawater desalination (Lahnsteiner, 2005).

Another industry which has employed water reuse is the textile industry. Large amounts of water are used throughout many textile operations including the production of dyes, fabric preparation, and washing of the fabric after each step. According to the United States EPA, a textile unit producing 9,000 kg/day of fabric consumes 36,000 liters of water (Shaikh, 2009). Not only does the textile industry consume large quantities of water, but valuable and persistent chemical products are discharged at a high rate. Recycling strategies can not only conserve water, but also help in the recovery of valuable chemical products. Schoeberl, Brik, Braun, and Fuchs published a case study in 2004 which developed a recycling concept for a specific textile processing case (the specific company/textile mill was left confidential).

In this case study, the standard of treatment for the effluent wastewater was a water quality to be reused directly into the textile industry process. In order to achieve this, a multi-stage process requiring combinations of biological and physicochemical techniques was applied. Effluent water treated from the textile mill was taken both from the final outfall where all the wastestreams were combined and from the washing process, where a specific waste stream could be isolated. Treating the water solely from the final outfall was more desirable, but more costly. The washing process waste stream, although easier to treat, contained significant amounts of oily substances. The main processes evaluated in this case study to treat both types of effluent water were membrane bioreactors (MBRs), oxidative processes, and ultrafiltration and nanofiltration

units. For the end-of-pipe effluent water, a combination of the MBR and nanofiltration process was determined to be most effective. The MBR reduced COD significantly (75-91%), but required nanofiltration to fully remove color and conductivity to adequate levels. For the washing water effluent, ultrafiltration tests were performed and rejection of COD and lipophilic substances were monitored. Rejection of COD was consistently above 75% and removal rate of lipophilic substances was even greater at above 83%. In conclusion, MBR treatment, nanofiltration, and ultrafiltration were all beneficial methods in treating industrial wastewater from textile processes.

The third and final example for industrial reuse is from the hydraulic fracturing industry. Hydraulic fracturing is the process of pumping millions of liters of water, sand, and other chemicals underground into tight shale rock formations in order to release the oil and gas to the surface. Hydraulic fracturing produces large amounts of wastewater, known as produced water, which traditionally has been disposed of in deep injection wells. However, as water treatment technologies become more affordable, disposal wells fill up, and regulations increase, produced water has been treated and reused more frequently.

How the produced water is treated and reused depends on the shale being fractured and quality of the produced water. For example, according to the EPA's 2011 Technical Workshops for the Hydraulic Fracturing Study proceedings, the Chesapeake Energy Corporation hydraulically fractures four different types of shales, with four different water qualities, requiring four different levels of treatment for reuse (Mantell 53, 2011). Depending on the type of reuse, Chesapeake Energy Corporation can decide to use conventional treatment (flocculation, coagulation, sedimentation, filtration, lime softening) or pair conventional treatment with more

advanced treatment technologies (reverse osmosis, thermal distillation, evaporation) to achieve a more pure water quality.

Generally, reuse of produced water involves the recycling of produced water to fracture more shale plays. In these cases, it is often necessary to only remove the suspended solids from the produced water in order to recycle it. Talisman Energy USA Inc. claims to have successfully operated using blended frac solutions of produced water where the only treatment applied was physical settling. In their case study published by the EPA, all particles greater than 30 micron were settled out of the produced water solution based on Stoke's law. A blended frac solution of approximately 50,000 mg/L TDS was used from this treated water with no apparent negative impacts on the formation of gas production (Minnich 62, 2011). If certain ions like barium, calcium, magnesium, and strontium do create scaling or hardness problems, sodium sulfate, soda ash, and lime are required to remove these metals (Minnich 61, 2011).

Though energy companies have largely been hesitant to use recycled frac waters with such high TDS concentrations, the cost effectiveness compared to using treated produced water which matches fresh water quality is drastic. Removal of TDS is a very energy intensive process, especially for produced waters that can have TDS concentrations as high as 260,000 mg/L. Still, if produced water is to be reused for any other purpose other than reuse in hydraulic fracturing, more rigorous treatment is required. In the Barnett shale play, mechanical vapor recompression thermal distillation process is the most capable alternative as it can handle a wide range of brines (10,000 mg/L – 120,000 mg/L TDS) while achieving over 70% efficiency in water recovery. Reverse osmosis is also another viable option. Reverse osmosis has achieved 60% recovery for TDS concentrations below 40,000 mg/L TDS (Hayes 70, 2011).

Using these case studies from various industries, certain water treatment technologies and methods were identified for further research. Feasibility to Ball Corporation's case and accessibility to bench scale treatment methods influenced which treatment methods were selected for further research. The following section of the literature review focuses on the technologies researched, tested, and proposed to Ball Corporation during the course of the study.

### **2.3. Review of Treatment Technologies**

After reviewing the literature and analyzing other industrial wastewater reuse case studies, different water treatment technologies were researched individually to determine the best options for Ball wastewater in Fairfield, CA. Of the researched options, five technologies are present in the final treatment train in some capacity. These five technologies are electrocoagulation, dissolved air flotation, ultrafiltration, granular activated carbon, and reverse osmosis. The following section of the literature review presents the research collected on these five technologies.

#### *2.3.1 Electrocoagulation*

Electrocoagulation is an electrochemical method of treating polluted water whereby sacrificial anodes corrode to release active coagulant precursors (usually aluminum or iron cations) into solution (Holt, 2004). This alternative to traditional chemical dosing of coagulants has been used in water treatment since 1887 (Vik 1355, 1984). Today, electrocoagulation is typically used in small wastewater treatment operations due to availability of chemical coagulants. It has been successfully applied to municipal wastewater operations, however, in the past. In 1911, electrolytic wastewater treatment plants were used in Santa Monica, CA, and were praised for their relative lack of odor and high quality effluent (Vik 1355, 1984).

Electrocoagulation follows the same principles of treatment as chemical coagulation with ferric chloride or alum, but does so through electrolysis. Instead of chemical coagulants such as ferric chloride ( $\text{FeCl}_3$ ) or aluminum sulfate ( $\text{Al}_2(\text{SO}_4)_3$ ) disassociating in water to form the aqueous coagulating agents,  $\text{Fe}^{3+}$  and  $\text{Al}^{3+}$  are directly corroded off the sacrificial anode. At the same time, the cathode produces small amounts of hydrogen gas through hydrolysis that occurs due to the electric current. As wastewater flows past the anode and cathode plates, it mixes with the dissolved coagulant and flocculation begins. The dosage of coagulant added can be controlled according to Faraday's law. Coagulant dosage can be increased by raising the electric current density or adjusting the time the sacrificial anode is in contact with the wastewater, by either slowing the flow rate or increasing the batch time (Vik 1356, 1984).

Electrocoagulation is different from chemical coagulation in a number of ways. It provides the advantage of less chemical handling, which Ball Corporation found very beneficial. Depending on the size of the electrodes used as well, replacement generally occurs on a yearly basis (Vik 1360, 1984). Electrocoagulation does increase electricity usage compared to chemical coagulants, but this added cost is likely recovered through a decrease in sludge production and disposal. Because iron or aluminum cations are directly produced without the addition of their anions, fewer solids are formed but the same coagulation process is achieved. In theory, operation and maintenance of the system should be simpler and require less technical expertise and oversight than chemical coagulant addition.

WaterTectonics<sup>TM</sup>, a water treatment company based out of Everett, WA, provided the electrocoagulation equipment used for this study. The diagram on the following page shows WaterTectonics<sup>TM</sup> interpretation for the electrocoagulation process.

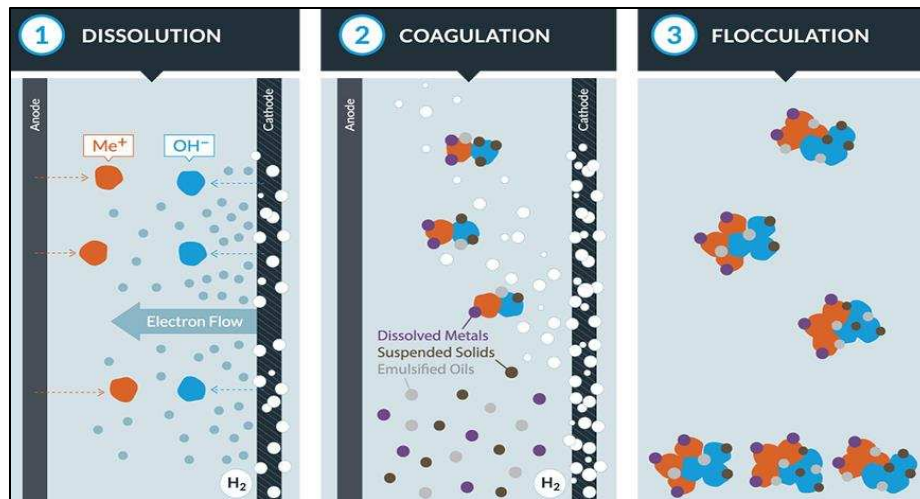


Figure 2.1: Dissolution, Coagulation, and Flocculation of Electrocoagulation Process - Copyright WaterTectonics

### 2.3.2 Dissolved Air Flotation

Dissolved air flotation (DAF) is a physical/chemical method of pretreatment for municipal and industrial wastewaters. DAF systems remove oils & greases, suspended solids, and biological oxygen demand very effectively. For the past fifty years, DAF systems have been frequently used to provide wastewater pretreatment, product recovery, and thickening of biological solids in industries ranging from food processing to pulp and paper to petrochemicals (Ross).

DAF systems operate to form waste sludge through two main processes: adsorption and flotation, and settling. The wastestream first flows into a contact cell chamber where the coagulant is applied. After application, the water with the coagulant flows into a large, generally rectangular separation tank where sludge is produced. In the separation tank, contaminants can either adsorb to pressurized microbubbles and float to the surface, or settle to the bottom of the tank. Surface sludge is removed by a skimmer, which removes the floating sludge at the outlet of the tank. Settled contaminants are removed by an auger at the bottom of the tank (Ross). Both sludges are combined together into one wastestream that can be filter pressed and disposed

of in later processes. Treated water flows out of the DAF through an effluent discharge chamber (Ross). Figure 2.2 below shows the basic components of a typical, industrial DAF unit.

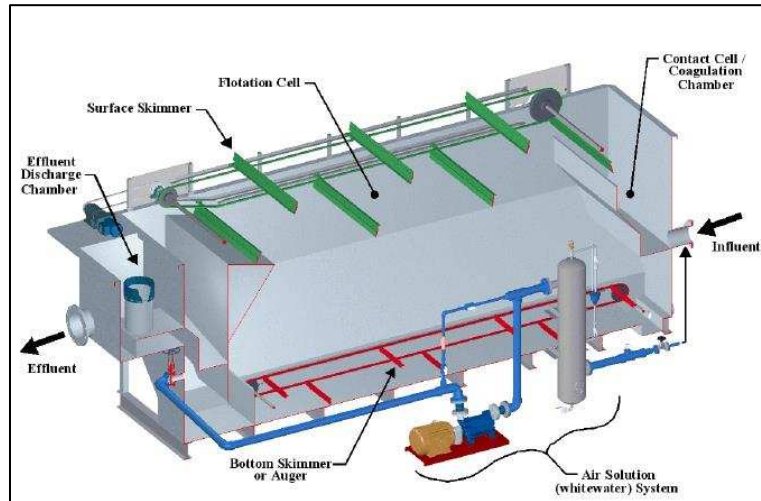


Figure 2.2: Typical DAF System Including Skimmer and Coagulation Chamber (Ross)

DAF operations are beneficial in removing a variety of contaminants from large flows of water. Advantages for DAF over traditional settling processes include better treated water quality, rapid start up, high rate operation, and a thicker sludge (Rodrigues 1). DAF is an excellent pretreatment process before any type of filtration is applied to the wastewater. With little operation and maintenance, DAF can remove a high amount of suspended solids and reduce fouling in later treatment steps. DAF can also be combined with multiple different types of combinations of coagulants to provide flexibility to the operation. At the Ball manufacturing plant in Fairfield, a DAF treatment system is the final treatment applied before the wastewater is discharged to the municipal wastewater treatment plant.

### 2.3.3. Ultrafiltration

Ultrafiltration is an advanced method of water treatment used to remove small colloids, bacteria, and other undissolved contaminants. In the past two decades, ultrafiltration has been one of the most important technological advances in water treatment due to its small amount of



required floor space and high removal rate (Chew et al. 3153). Differences in pore size are the only variable that determines the three different types of membrane filtration (microfiltration, ultrafiltration, and nanofiltration). Ultrafiltration is the middle of the three types with an average pore size between 0.05-0.5  $\mu\text{m}$ ; still fine enough to remove 99% of turbidity or suspended solids (Chew et al. 3153). This level of removal has made ultrafiltration a common treatment technique in both drinking water and industrial water treatment plants around the world.

Ultrafiltration can be operated in a number of different ways. Ultrafiltration through direct filtration pressurizes the wastestream directly through the filter in a dead end operation. Alternatively, a crossflow technique can be utilized where the wastestream flows parallel to the membrane and is recycled continuously across the membrane. However, of all the different methods, hollow fiber ultrafiltration methods are most commonly used to filter larger quantities of wastewater. Hollow fiber filters maximize membrane surface area and conserve floor space. Hollow fiber membranes are placed in chambers containing the wastewater. When the chamber is pressurized, wastewater is forced into the hollow fibers and flows up through the fibers and to the outlet. Figure 2.3 below shows a series of GE ultrafiltration hollow fiber membranes.



*Figure 2.3: GE Hollow Fiber Ultrafiltration Membrane Series (GE Water)*

Ultrafiltration membranes can be manufactured from a number of different materials including ceramics and polymers. By selecting the optimal material and pore size for the type of wastewater to be filtered, fouling of the ultrafiltration membrane can be reduced (Chew et al. 3153). Membrane fouling is the result of foulants and particles building up on the membrane surface, plugging the membrane pores, or adsorbing within the membrane pores (Walker 228). When an ultrafiltration membrane fouls, flux through the membrane is reduced, removal rate may drop, and costs rise. Periodic backwashing and adequate pretreatment can reduce fouling of ultrafiltration membranes, but over time permanent fouling will take place and membranes will have to be replaced entirely.

Fouling of ultrafiltration membranes is one of the main operational concerns in ultrafiltration. Organic matter is one of the main contaminants known to foul organic membranes significantly (Walker 228). Relatively high costs compared to traditional media filtration processes are another reason ultrafiltration has not become widely used in water treatment (Chew et al. 3153). However, due to improvements in production of membranes, ultrafiltration and other advanced membranes may become more commercially viable than conventional systems (Chew et al. 3161).

#### *2.3.4. Granular Activated Carbon*

Granular activated carbon (GAC) is a specialized form of carbon designed to have low-volume pores to increase the surface area and adsorb dissolved contaminants. Adsorption with GAC has become a widely accepted form of treatment for removing organic contaminants from groundwater, wastewater, and industrial wastestreams (Stenzel, Merz 257). GAC is cost-effective and applicable process for natural organic matter (NOM) removal in drinking water treatment plants (Gibert et al. 2821). GAC filters are not only used for large scale water

treatment, but also localized water purification. GAC and powder activated carbon (PAC) systems are widely available in commercial forms for homeowners to purchase and install in their refrigerators and homes.

GAC is essentially a specialized form of charcoal. Through chemical and physical processes, GAC producers are able to drastically increase the amount of pore space in common charcoal to provide much more adsorption capacity. When wastewater flows through a GAC filled column, contaminants, especially organic contaminants, are adsorbed and trapped inside the abundance of pores. GAC filters can either be operated as purely physical, adsorption water treatment processes, or as a biological process as well. By allowing bacteria to form in GAC filters, biodegradation can contribute to the overall NOM removal. Over time, progressive clogging of GAC filters takes place as pore space is exhausted and biological material increases overall head loss (Gibert et al. 2822). When this occurs, GAC must be either regenerated or replaced to recover its adsorption capacity.

GAC adsorption can be optimized by selecting the most effective GAC pore size's that match the organic material targeted for removal (Gibert et al. 2822). Considerable efforts have been made in prior studies to determine the relationship between NOM constituents (molecular weight, degree of hydrophobicity, and charge distribution) and physical properties of different types of GAC (surface area, porosity, etc.). However, much remains unknown about the sorption behavior of NOM constituents or groups (Gibert et al. 2822). Optimal sorption can be achieved by lengthening contact time between wastestream and GAC, preventing clogging of the filter, and pretreating the wastestream with coagulation, DAF, or ultrafiltration. Studies have shown that ultrafiltration in particular, when combined with GAC treatment, can make an excellent pretreatment for reverse osmosis and other advanced water treatment processes (Monnot et al. 1).

The table below from Monnot’s study on granular activated carbon combined with ultrafiltration as a pretreatment for seawater reverse osmosis shows how effective GAC treatment can be in any form. GAC filtration can not only remove dissolved organic carbon (DOC) but also reduce turbidity.

*Table 2.1: Reported Studies with GAC Filter Bed as Pretreatment before Seawater Reverse Osmosis (Monnot 2)*

Lab-Scale Treatment Type	Impact on Water Quality
GAC Biofiltration + Submerged Microfiltration + Reverse Osmosis	> 70% DOC Removal
GAC Filtration + Reverse Osmosis	< 0.3 NTU
20 Days of GAC Biofiltration	70% DOC Removal
75 Days of GAC Biofiltration	39% DOC Removal
GAC + Submerged Microfiltration	63% DOC Removal

### 2.3.5. Reverse Osmosis

Reverse osmosis (RO) is one of the most advanced forms of water treatment. RO targets the removal of dissolved solids by overcoming osmotic pressure. Industries that often require ultrapure water include semiconductors, laboratory services, pharmaceuticals, and cleanroom laundries. RO is also one of the key water treatment processes in seawater desalination. Seawater often contains total dissolved concentrations above 30,000 mg/L and reverse osmosis is often one of the most energy efficient processes to remove this high total dissolved solid (TDS) load to produce potable water. Today there are over 21,000 reverse osmosis desalination plants in operation around the world with the Middle East providing a growing share of the total demand (Poseidon Water). Worldwide, desalination plants treat and produce 13.2 billion liters of potable water each day (Poseidon Water). As dry, coastal areas continue to grow, desalination plants and reverse osmosis will become more necessary technologies to provide adequate supply to meet water demand.

Reverse osmosis operates by highly pressurizing feed water to exceed the natural osmotic pressure. When osmotic pressure is exceeded, feed water may be forced through a

semipermeable membrane. Although RO is similar to other membrane applications, separation efficiency is not dependent on the pore size, but instead on solute concentration, pressure, and water flux rate. Water molecules must individually diffuse through the semipermeable membrane. Semipermeable membranes can be constructed from a variety of different materials. Membranes can be fabricated from many different polymers, can have cellulose films, and can even be combined with filtration membranes to create composite membranes (Petersen 81). General Electric, DOW, Toray, and TrisSepts are just a few of the companies who produce many different types of reverse osmosis membranes. Different membranes are designed to operate at a variety of pressures, pH ranges, fluxes, rejection rates, and influent water qualities. With so many variables and parameters to keep track of, computer models have been developed to predict RO operation. The main interface for General Electric’s modeling software, WinFlows, is shown in the figure below.

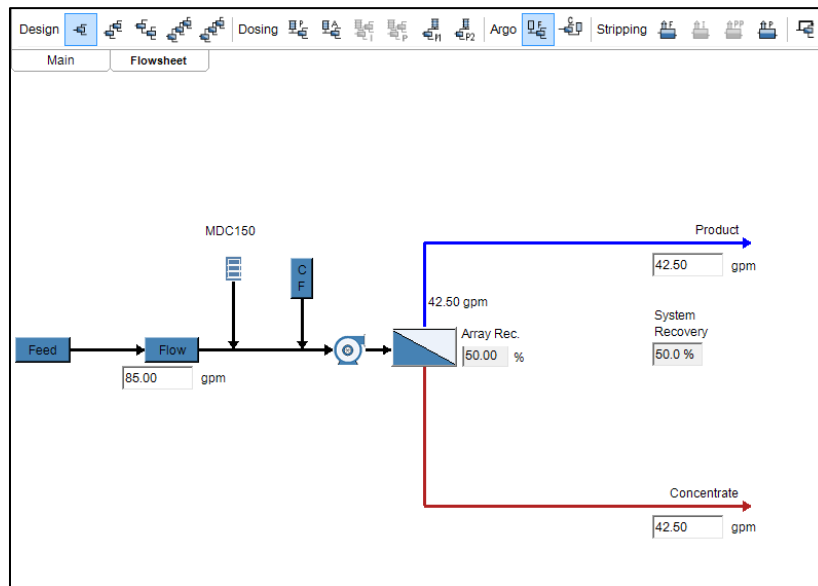


Figure 2.4: WinFlows Main Interface (GE Water)

Like membrane filtration processes, reverse osmosis can be operated in a dead-end process or a cross flow operation. Either option produces the waste from the reverse osmosis

process: brine. Brine is the highly contaminated, high TDS wastewater which accepts all the contaminants removed from the clean, permeate water. In desalination operations, brine water is often piped out deep into the ocean to allow for dilution of the brine.

Because it is one of the few water treatment processes able to remove TDS, reverse osmosis is an extremely valuable process. RO allows for a variety of removal rates and can be automated for much of its operation. However, RO has some limitations. Extensive pretreatment, including some form of membrane filtration, must be included in order to prevent immediate fouling of the RO membranes. Membrane fouling deteriorates the performance of membranes by reducing overall flux and impairing effluent water quality which then increases both capital and operational costs (Tang et al. 330). High energy requirements and technical expertise also make RO operations difficult to implement. However, studies have shown through economic analysis that the investment in RO systems can be cost-neutral with current estimates for associated expenses in some industries (Petricin 299). Like membrane filtration processes, RO membranes are becoming more feasible as producers become more adept at membrane production and scarcity of traditional water sources increases.

#### **2.4. Purpose & Objectives**

The severe drought in California has caused many individuals, corporations, and other institutions to evaluate their water resources. Ball Corporation understands the necessity of available, high quality water in its can manufacturing process. Ball Corporation also understood that a unique opportunity to become a corporate leader in the field of industrial water reuse was available to them. As part of their sustainability goals, Ball Corporation wished to pursue ways in which their manufacturing operations might become more environmentally friendly. Ball Corporation approached Colorado State University with the purpose of understanding how their

business can better reuse and manage water in not only their Fairfield manufacturing plant in California, but all over the world. Ball Corporation The purpose of this study was to evaluate Ball Corporation's current production process and present them with an assessment for how their operations could be feasibly altered to conserve water resources.

The objectives for the project as determined by Dr. Sharvelle and Dr. Carlson in May 2015 are as follows:

- 1) Using Ball Corp. manufacturing plant in Golden, CO as the initial study site, develop scenarios (wastewater quality and water quality goals) and simple models for recycling plant wastewater for beneficial use. Based on identified recycling scenarios, define potential treatment processes to achieve goals.
- 2) Conduct bench scale and/or pilot scale testing of treatment processes defined in 1). Define treatment trains that will accomplish water quality goals using wastewater from Golden plant.
- 3) Based on recycling scenarios and lab testing, develop cost model for Golden plant to encompass alternatives for recycling including beneficial use and fraction of water recovered.

Since these initial objectives were first brought to Ball, the only change has been the plant location to be analyzed. Instead of studying the manufacturing plant in Golden, CO, the Fairfield, CA, plant was chosen based on the impact caused by the California drought.

## CHAPTER 3: PHASE I: FAIRFIELD WATER AUDIT

### **3.1. Objectives of Water Audit**

The first step in this study was to conduct a water audit on the Fairfield plant. This water audit was necessary to fully understand the Fairfield plant's operation, its water flows in terms of flow quantity and water quality, and what possible options were available to recycle effluent water. This water audit was completed in July 2015 and formed the basis to the later developments and decisions in this study. Without the initial water audit, a complete, well informed final proposal to Ball Corporation would not have been possible.

The main sections of this Phase I report focus on the water audit of the current facility (where water flows, how much, and of what quality), the current water quality being supplied and discharged by the plant to the POTW, and specific water treatment processes which were further analyzed in Phase II. Bench scale test methods to analyze these specific water treatment processes are suggested to further analyze their effectiveness. These bench scale tests were completed as part of Phase II of the study and are presented in Chapter 4 of this thesis.

### **3.2. Fairfield, CA – Metal Beverage Packaging Division Plant**

The Ball manufacturing plant is located in Fairfield, CA, a city of about 100,000 people halfway between Sacramento and San Francisco. Like many of Ball's manufacturing plants, the Fairfield plants operates very rapidly; in 2014 Ball reported 2.3 billion cans produced from the plant. This level of production, however, required 114 million liters in 2014, costing the plant about \$172,000. This municipal water is used in a variety of plant operations. Accounting for these different water uses was the first step in the water audit. After accounting for the different



uses and quantifying the flows, water quality data was then acquired, and analyzed to optimize the most efficient methods to recycle effluent water.

### **3.3. General Water Audit of Plant**

Approximately 85 GPM of municipal water flows into the plant when in operation. This water is then divided into separate flows for separate purposes. Some of the water is boiled to heat the building, some is used to cool equipment throughout the plant, but most is used in the three washers on the three production lines. Of the 85 GPM brought in by the plant, approximately 68 GPM are used in the three washers. This accounts for 80% of the plant's water usage.

The three washing lines use 21 GPM, 26 GPM, and 21 GPM respectively, adding up to 68 GPM. These washers have six different washing/rinsing stages. The first five stages use municipal water, and in the sixth stage, deionized water from an ion exchange unit is used to completely rinse and sterilize the cans. During the washing process, the water is adjusted at each stage for different pH levels and collects contaminants off of the aluminum cans. After flowing through the washers, the majority of the water enters the oil break (some of the wastewater skips the oil break and flows directly to the reaction cells). At the oil break, oils and greases are removed from the effluent through de-emulsification. After the oil break, the wastewater flows into reaction cells. These four reaction cells adjust the effluent pH level to meet the city discharge requirements. Finally, the water flows into the dissolved air flotation (DAF) unit. Here, MegaFloc is added as an organic coagulant. The DAF unit removes solids with an auger at the bottom of the tank and oils with a skimmer at the surface. Much of the MegaFloc coagulant is removed on the surface with the skimmer, but some was clearly able to escape the DAF unit with the treated water. After flowing through the DAF, the effluent water is measured using a V-

notch weir at Outfall II. Following the weir, water used to cool the machinery is added to the washer water effluent and discharged to the POTW. This brings the total amount of effluent water discharged through Outfall II to approximately 79 GPM.

The schematic on the below (Fig. 3.1) shows the general layout of water flows throughout the Fairfield plant. Blue boxes represent existing infrastructure, while the red box and arrows represent the proposed recycling and treatment processes. Because washer water consumes 80% of the influent, the CSU team decided it was the most feasible to isolate and focus on treatment for recycling. The boiling and cooling lines are relatively small and are already very efficient. Therefore, only the washer water (which contributes to 80% of the plant's water use) would be connected to any proposed treatment and recycling system.

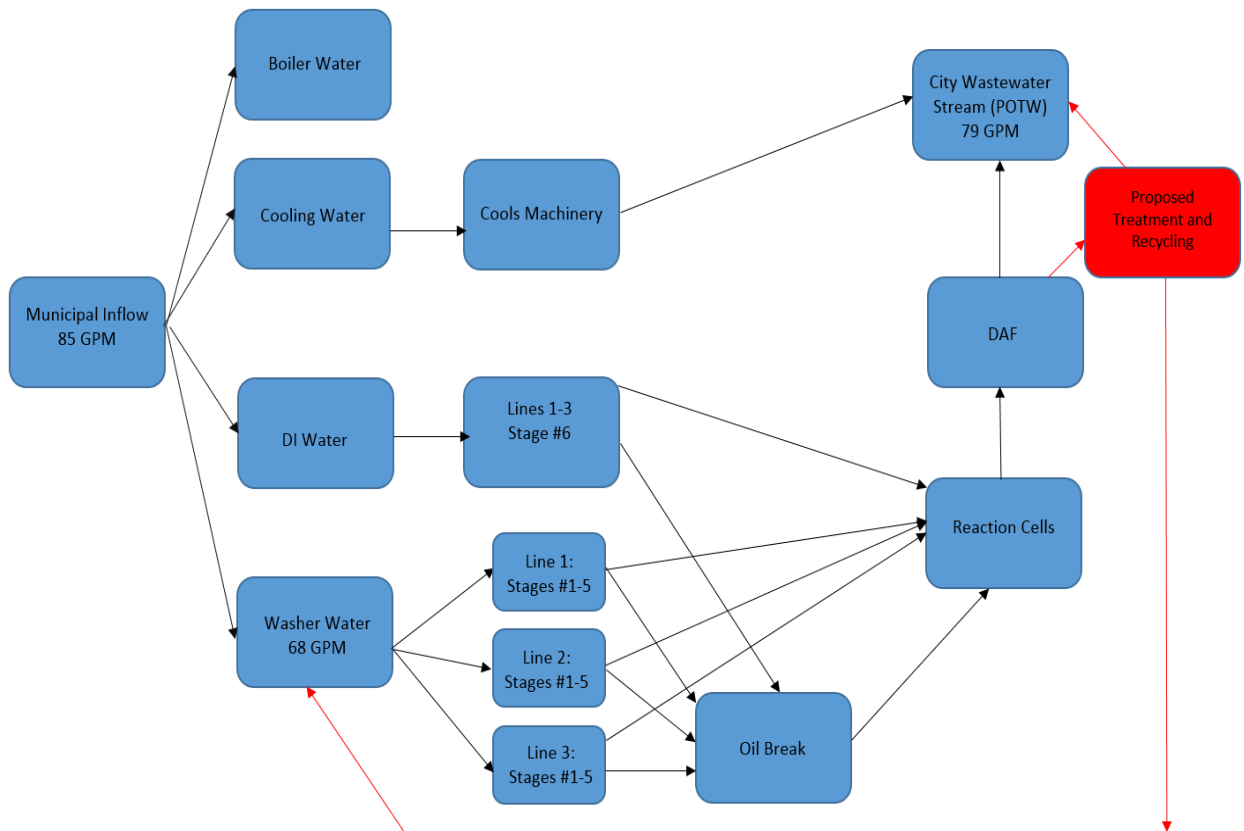


Figure 3.1: General Fairfield Plant Water Flow Schematic for Entire Plant

### 3.4. Washer Audit of Plant

After the general plant water audit, a more specific analysis of the three can washers was conducted. A washer flow schematic (Fig. 3.2) is shown on the following page. In Figure 3.2, the six different stages are shown, along with the drag out tanks, and the counter flow mechanisms. The six stages are the prewash (Stage 1), wash (2), 1<sup>st</sup> rinse (3), 2<sup>nd</sup> rinse (4), final rinse (5), and DI rinse (6). Of these six stages, municipal water is pumped into Stages 1, 2, and 5 at a rate of approximately 21-26 GPM per washer. DI water is pumped into Stage 6 exclusively and re-circulated until the conductivity exceeds 130  $\mu\text{S}/\text{cm}$  at which point the DI water must be retreated and replaced. Ion exchange units currently treat municipal water to supply the DI water for the final rinse.

Attached to Stage 3 and 5 are drag out tanks that help to conserve water by allowing a space for water to collect and be moved through a counter flow process. The counter flows (shown as red curved arrows in Fig. 3.2) also help to conserve water by reusing water from later stages in earlier stages. Also in Fig. 3.2 are the wastewater flows to reaction cell #1 and the oil break. Most of the wastewater from the washers goes to the oil break and then the reaction cells, as shown by the grey arrows. However, L1 Stage #2, L2 Stages #2, 5, 6, and L3 Stages #2, 5, 6 wastewaters skip the oil break and directly enter reaction cell #1, as shown by the brown arrows. From reaction cell #1, all of the washer effluent flows into the three other reaction cells, the DAF, Outfall II, and finally to the Fairfield POTW.

Each stage of the washer also has its own specific requirements in terms of pH, conductivity, and temperature. Table 3.1 and 3.2 show these specifications. It should be noted that Drag Out #2 is the only tank with no requirements. Water in this drag out is very similar to the initial water used in Stage 5 so it is not necessary to monitor it. Also of note are the large

swings in pH the cans undergo through the washing process. Initially, cans are prewashed with very acidic water and then cleaned with very basic water. pH somewhat stabilizes by Stage 5, but the initial pH swings are important to acidify and then cleanse any residue on the surface of the can. Very few differences exist between Line 1 & 2 specifications versus Line 3. Following these tables is Figure 3.2, which as mentioned, shows the washer flow layout and flow quantities.

*Table 3.1: Line 1 and Line 2 Specifications – 12oz Cans (As Reported by the Fairfield Plant)*

Stage	pH	Conductivity (µS/cm)	Temperature (°F)
1	1.8 – 2.0	4.2	120 - 140
2	11.55 – 11.85	10.5	110 - 125
3 (Drag Out #1)	1.75 – 1.95	N/A	115 - 130
4	N/A	470 (1000 Max)	N/A
5	4.0 – 4.5	500	N/A
6	N/A	40 – 130	N/A

*Table 3.2: Line 3 Specifications - 12oz Cans (As Reported by the Fairfield Plant)*

Stage	pH	Conductivity	Temperature
1	1.8 – 2.0	4.2	120 – 140 (115 – 125 for 7.5oz and 5oz cans)
2	11.7 – 12.0	10.5	110 - 125
3 (Drag Out #1)	1.75 – 1.95	N/A	115 - 130
4	N/A	470 (1000 Max)	N/A
5	4.0 – 4.5	500	N/A
6	N/A	40 – 130	N/A

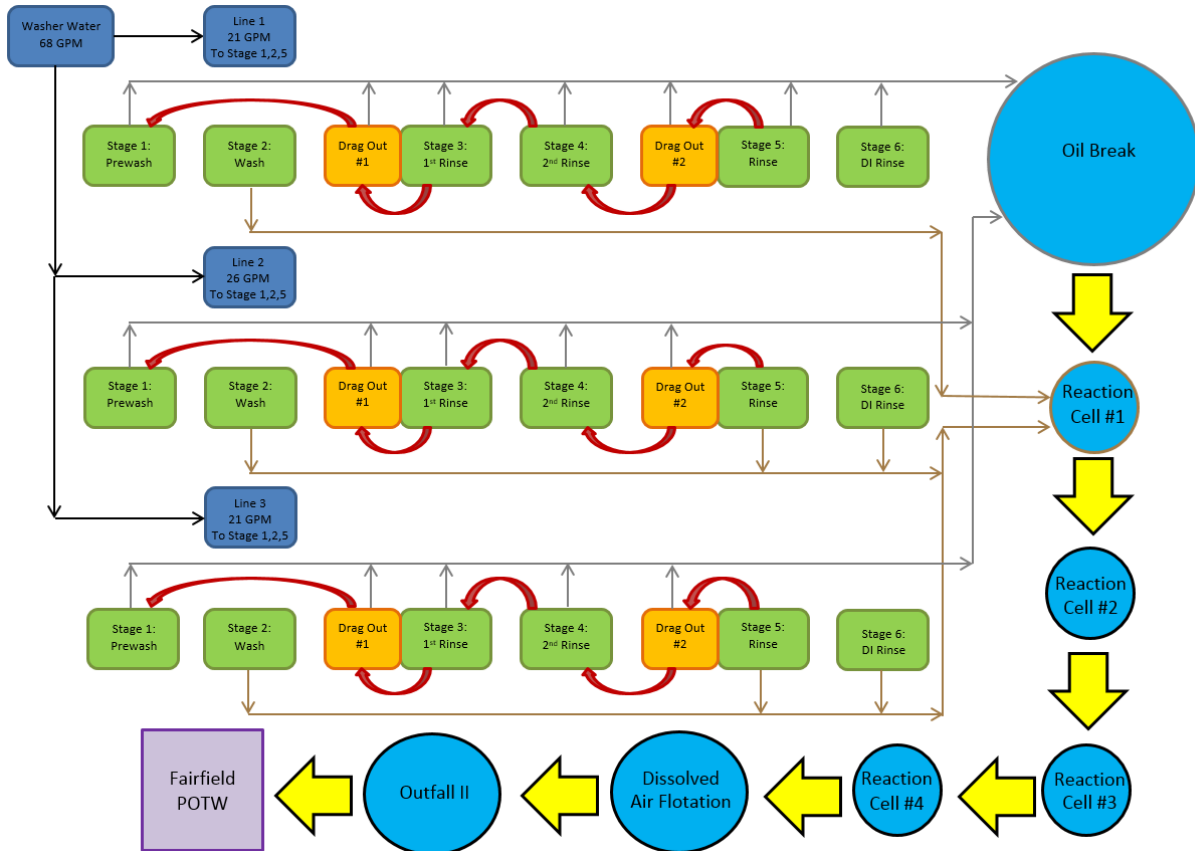


Figure 3.2: Fairfield Washer Water Flow Schematic – Lines/Washers 1-3

### 3.5. Water Quality Data

To fully complete the water audit, not only did the flows have to be separated and quantified, but also tested for specific water quality parameters. The influent and effluent water qualities were determined through records received from the Fairfield plant managers, lab testing done at CSU, and lab testing performed at ALS Laboratories in Fort Collins, an EPA certified lab.

The two types of water tested were the influent municipal water and the effluent water from Outfall II. These samples were tested in order to understand the degree of treatment required to recycle the effluent in the washers to closely match the influent municipal water quality. Cooling and boiling waters were not tested due to their relatively small flows in the plant and lack of chemical reactions. The DI water was also assumed to be almost completely

pure with extremely low solids concentrations so it was also not tested. Grab samples of water in between washing steps are possible future samples that could be tested to better understand how the washing process affects water quality.

On the following page in Table 3.4 are water quality results for the Fairfield municipal water ( $WQ_{in}$ ) and Outfall II water ( $WQ_{out}$ ). Water quality parameters for influent and effluent sources were acquired from four different sources. Caltest Analytical Laboratories is a State of California certified analytical lab with whom the Ball Fairfield plant had contracted with to test its industrial wastewater data. Parameters tested by Caltest are highlighted in blue in Table 3.3. Municipal drinking water parameters are reported by the City of Fairfield and are highlighted in green. These municipal water quality values come from the City of Fairfield's 2013 Consumer Confidence Report. Parameters tested by Colorado State University in the environmental lab are highlighted in yellow. These parameters were tested in June 2015 with initial water samples shipped from Fairfield to CSU. Finally parameters tested by EPA certified ALS Laboratories are highlighted in red. Some municipal water quality parameters were deemed negligible and not tested. These parameters are marked as N/A.

Table 3.3: Water Quality Results – From Multiple Sources and Labs, CSU Tested Parameters from Single Sample in June 2015

Parameter	Municipal Water - WQ <sub>in</sub>	Outfall II - WQ <sub>out</sub>
Fluoride	0.894 mg/L	1.3 mg/L
Copper	N/A	0.022 mg/L
Manganese	N/A	0.026 mg/L
pH	7.97	9.67
Conductivity	346 $\mu$ S/cm	6160 $\mu$ S/cm
Salinity	N/A	3,080 mg/L as NaCl
COD	N/A	370 mg/L
Alkalinity	120 mg/L as CaCO <sub>3</sub>	180 mg/L as CaCO <sub>3</sub>
Turbidity	0.065 NTU	16.1 NTU
Total Organic Carbon (TOC)	2 mg/L	110 mg/L
Dissolved Organic Carbon (DOC)	(Same as TOC)	104 mg/L
Total Dissolved Solids (TDS)	306 mg/L	4,900 mg/L
Total Suspended Solids (TSS)	<10 mg/L	34 mg/L
Total Volatile Solids (TVS)	N/A	186 mg/L
Oil & Grease	N/A	8 mg/L
Total Petroleum Hydrocarbons (TPH)	N/A	3.8 mg/L
Hardness	133 mg/L	140 mg/L

The water quality results show significant differences between the influent and effluent. Parameters of most concern related to recycling the effluent are TOC, oil & grease, TDS, conductivity, and turbidity. These five parameters pose the most serious issues in terms of treating and recycling the effluent water. Salinity and COD measurements also increase significantly, but are accounted for in conductivity and TOC. Alkalinity and hardness measurements also show increases. Both conductivity and TDS measure dissolved concentrations of ions, but are both beneficial to monitor due to different measuring techniques in the field and in the lab. As a percentage, increases in the five main parameters of concern are shown in Table 3.4 below.

Table 3.4: Change in Water Quality, Influent to Effluent (Based on Table 3.3 Parameter Results)

Water Quality Parameter	Conductivity ( $\mu$ S/cm)	Turbidity (NTU)	TOC (mg/L)	TDS (mg/L)	Oil & Grease (mg/L)
% Increase (WQ <sub>in</sub> to WQ <sub>out</sub> )	1780%	24769%	5500%	1601%	>5000%

### 3.6. Discharge Water Quality Requirements

Recycling any amount of water will reduce the amount of water required and discharged by the Fairfield plant. Therefore, discharged water from the Fairfield plant to the municipal wastewater facility will contain higher concentrations than before treatment and recycling. The City of Fairfield has created restrictions for wastewater discharge that still need to be met if water treatment and water recycling are to be implemented.

According to FAIRFIELD-SUISUN SEWER DISTRICT ORDINANCE NO. 2008-03 (Fairfield’s wastewater discharge ordinance), the pH of any waste stream must be between 6-11, lower than 130 °F, and not contain BOD levels, solids, or oils which could cause an interference in the municipal wastewater treatment process. Industrial users must comply with national categorical pretreatment standards found at 40 CFR Chapter I, Subchapter N, Parts 405–471, and state pretreatment standards found in the Porter-Cologne Water Quality Control Act, California Water Code, Division 7. Table 3.5 contains a list of local contaminant limits.

*Table 3.5: Local Contaminant Limits as Reported by City of Fairfield*

Contaminant	Daily Maximum Limit (mg/L)
Arsenic	0.1
Cadmium	0.05
Chromium	0.15
Copper	1.3
Cyanide	0.7
Lead	0.5
Mercury	0.01
Nickel	0.9
Oil and/or Grease of Mineral or Petroleum Origin	100
Oil and/or Grease of Animal or Vegetable Origin	300
Silver	0.2
Total Identifiable Chlorinated Hydrocarbons	0.02
Total Petroleum Hydrocarbons	50
Total of Benzene, Toluene, Ethylbenzene, and Xylenes	25
Phenols	1.0
Zinc	2.3



### **3.7. Treatment and Recycling Goals**

Based on the water audit from the Fairfield plant, initial treatment goals were brainstormed by the combined CSU and Ball Corporation team. Ball Corporation desired a treatment system which would be relatively compact, reproducible at other manufacturing plants, not heavily reliant on chemical processes, and preferably able to be operated by a 3<sup>rd</sup> party in a design-build-operate fashion.

The first goal to determine was how much water should be recycled and from what sources. As discussed earlier, the washer water was quickly isolated as having the most opportunity for treatment and recycling improvement. As for the quantity treated and recycled, both CSU and Ball agreed to start with a conservative approach. Ball Corporation tried previous water treatment and recycling efforts in the past that had quickly failed due to overly ambitious and confident designs. A 50/50 split of recovered water to discharged water to the Fairfield POTW was agreed to be the base scenario. If proven successful, the recovery ratio could be increased in later experiments.

For water quality, both CSU and Ball were uncertain about the degree of treatment required to protect product quality and integrity. Ball Corporation has used different water qualities from around the world and had never studied the threshold for minimum water quality to produce a quality aluminum can. With this uncertainty, it was agreed that CSU would pursue a water quality as similar to Fairfield's municipal water quality as possible.

With these water quantity and quality goals in mind and the water audit of the Fairfield plant complete, the CSU team began proposing, researching, and testing bench scale water treatment processes. The following section concludes Phase I of the study and suggests treatment processes that were thoroughly tested in Phase II.

### 3.8. Proposed Process Analysis

After considering the water quality results, requirements, general feasibility, and goals of the project, the CSU research team determined a specific set of processes to treat and recycle the effluent water in the Fairfield plant. These processes and their corresponding bench scale testing options are described in Table 3.6 below.

Table 3.6: Suggested Treatment Processes and Testing

Process	Bench Scale Test	Bench Scale Alternatives	Contaminants Removed
Coagulation	Jar Tests	Ferric Chloride	Turbidity, TOC, oil & grease
		Aluminum Sulfate	
		Electrocoagulation	
Ultrafiltration	EMD Millipore Amicon™ Stirred Cells (Traditional Flow Method)	50 kDa (~0.04 μm)	TDS, turbidity, conductivity
	Sartorius™ Vivaflow 50 (Tangential Flow Method)	0.1 μm ultrafiltration	
		50 kDa (~0.04 μm)	
Reverse Osmosis	Sterlitech™ SEPA CF Cell	Synder Filtration™ Ultrafiltration – Series BN 50 kDa (~0.04 μm)	TDS, conductivity, salinity, hardness
		GE Osmonics™ Reverse Osmosis – Series SE	
		TriSep™ Reverse Osmosis - Series X201	

Coagulation was chosen as a tested process because of its frequent use in industrial water treatment, ability to remove a variety of non-dissolved contaminants, and reliability as a pretreatment for later, more delicate treatment processes. Coagulation also has the ability to remove turbidity, TOC, and oil & grease, three of the five most concerning water quality parameters.

Aluminum sulfate, ferric chloride, and electrocoagulation alternatives composed the different bench scale coagulation options most readily available and feasible. Aluminum sulfate (alum) and ferric chloride (iron) were chemical coagulation alternatives, while the electrocoagulation process from WaterTectonics™ provided an electrochemical alternative.

Ultrafiltration was selected as a proposed treatment process due to its small square footage requirements, growing popularity in all kinds of water treatment operations, and effective removal of all suspended solids and colloids. In addition, ultrafiltration can reduce turbidity down to effectively 0 NTU, which is necessary for later more delicate processes such as ion exchange or reverse osmosis. Of the five most concerning water quality parameters, ultrafiltration is the best at complete removal of turbidity, and can also remove oil & grease and TOC if these parameters make up any part of the total suspended solids concentration in the Fairfield wastestream.

Two different ultrafiltration methods, dead end filtration and tangential flow, were initially suggested for bench scale testing. The Millipore filter cell was used to test the traditional, dead end method, while Sartorius™ and Sterlitech™ units were suggested to test the tangential method. Both methods were tested by CSU with 50 kDa (0.04 µm pore) size membranes. 50,000 Daltons or 50 kDa is a useful level of ultrafiltration to set as a baseline because its pore size corresponds to a variety of available commercial ultrafiltration units. Though 50kDa is a fairly standard ultrafiltration pore size, a 0.1 µm pore size was also suggested.

Reverse osmosis was chosen because of its ability to remove dissolved contaminants, adjustability to a variety of different recovery rates, and relatively low TDS concentration in the Fairfield wastestream. Reverse osmosis was determined to be a preferred alternative to remove

TDS/conductivity after turbidity, oil & grease, and much of the TOC had likely been eliminated. Reverse osmosis also provided a means to easily adjust the recovery rate later on in the study by increasing the pressure or switching to a different membrane.

The CSU team first suggested using a Sterlitech™ SEPA CF Cell to test the reverse osmosis process. This cell operates as a tangential filter and can be used to test not only reverse osmosis, but also nanofiltration, ultrafiltration, and microfiltration membranes as well. Membranes from different companies specific to industrial wastewater were tested. By testing different membranes from different brands, permeate and brine water quality could be optimized.

Below are some of the lab equipment and instruments that were used to perform these bench scale tests (Figures 3.3-3.8):



Figure 3.3: Amicon Stirred Cell Ultrafiltration Unit

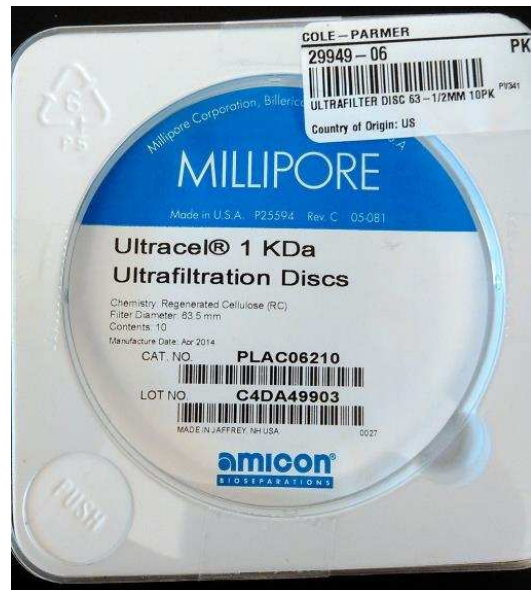


Figure 3.4: Millipore 1 kDa Filter (Ultrafiltration)

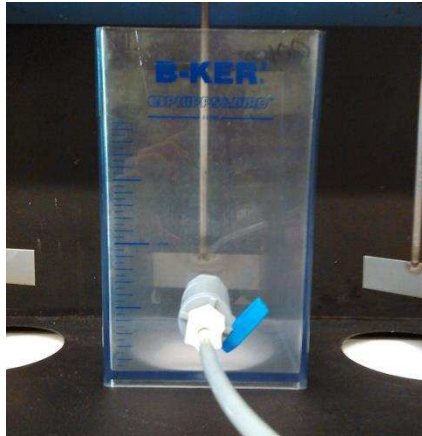


Figure 3.5: B-KER™ 2 Liter Mixing Jar (Coagulation)



Figure 3.6: Jar Test Mixer (Coagulation)



Figure 3.7: Sartorius™ Vivaflow 50 (Ultrafiltration)



Figure 3.8: Sterlitech™ SEPA CF Filter (Reverse Osmosis)

Figures 3.3 and 3.4 show equipment used in the ultrafiltration step. A Millipore filter was inserted into the Amicon™ unit and put under high pressure to perform the ultrafiltration procedure. Pictured is a 1 kDa Millipore filter that was eventually used, but 50 kDa filters as described earlier were mostly applied to dead end ultrafiltration testing. Figures 3.5 and 3.6 relate to the coagulation process. Figure 3.5 shows the jar used to hold tested water and coagulant, while Figure 3.6 shows the rapid mixer that was used to stir different coagulants into the Fairfield effluent water. Figures 3.7 and 3.8 are the tangential flow ultrafiltration and reverse osmosis units.

## CHAPTER 4: PHASE II: BENCH SCALE TESTING

### 4.1. Coagulation

Coagulation is the process of adding inorganic or organic chemicals to wastewater in order to neutralize negatively charged particles and create larger particles that can more easily be removed. As described in the Phase I report, ferric chloride (iron) and aluminum sulfate (alum) coagulants were tested as well as an electrocoagulation process. Many different trials were conducted to determine optimal concentration doses for each coagulant in order to remove as much turbidity as possible. Iron and alum coagulants were tested in two sets of trials to determine an optimal dose based on turbidity. Electrocoagulation was tested separately over a range of testing. The procedure and results for the chemical coagulants will be presented first, followed by electrocoagulation. Lastly, a discussion to compare the three different types of coagulants will conclude this section.

#### 4.1.1. Chemical Coagulants – Procedures and Results

Chemical coagulants were tested exclusively via jar tests. 1,000 g/L solutions of iron and alum coagulants were created for use as the coagulant stock solutions. In the first set of chemical coagulant tests, six concentrations of iron coagulant and six concentrations of alum coagulant were tested. Concentrations in this first set of tests were 25, 50, 100, 150, 200, and 250 mg/L for both coagulants. This broad range was used to narrow the optimal range for the second set of trials. Ball water was from the same grab sample (Sample #1 as seen in Appendix A) for all twelve trials (6 iron, 6 alum). Beakers were filled with 400 mL of Ball water and exact amounts of stock solutions to match each coagulant concentration trial were added. The equations on the following page show how stock solution volumes were calculated.

$$\text{Ferric Dosage } \left(\frac{\text{mg}}{\text{L}}\right) = \frac{\text{Desired Dosage } \left(\frac{\text{mg}}{\text{L}}\right) \times \text{Molar mass of FeCl}_3 \left(\frac{\text{g}}{\text{mol}}\right)}{\text{Molar mass of Fe } \left(\frac{\text{g}}{\text{mol}}\right)} \quad \text{Eq. 4.1}$$

$$\text{Stock Solution (mL)} = \frac{\text{Ferric Dosage } \left(\frac{\text{mg}}{\text{L}}\right)}{100} \times \text{Jar Test Volume (mL)} \quad \text{Eq. 4.2}$$

Stock solutions for each type of coagulant were added simultaneously and then mixed rapidly for 1 minute at 100 RPM, slowly mixed, or flocculated, for 10 minutes at 25 RPM, and then left to settle for 10 minutes. After separating the sludge, turbidity, conductivity, TOC, and pH were measured after filtering remaining larger colloids through a 6 $\mu$ m filter.

Results after both initial sets of jar tests can be seen below. The coagulated results were also compared to a blank. This blank had no coagulant added but was filtered through a 6 $\mu$ m filter. Results from this initial set of jar tests before 6 $\mu$ m filtration can be found in Appendix A:

*Table 4.1: Iron Coagulant Results – Set 1, Single Tests from Water Sample #1*

Parameter	Blank	Jar 1	Jar 2	Jar 3	Jar 4	Jar 5	Jar 6
Coagulant Dose (mg/L)	None	25	50	100	150	200	250
Turbidity (NTU)	0.37	1.20	2.26	6.12	78.30	134.00	159.00
Conductivity (mS/ $\mu$ m)	5.76	5.67	5.57	5.81	6.11	6.50	6.59
pH	9.23	7.45	7.29	4.48	3.20	2.90	2.74
TOC (mg/L)	120	115	113	115	114	116	115

*Table 4.2: Alum Coagulant Results – Set 1, Single Tests from Water Sample #1*

Parameter	Blank	Jar 1	Jar 2	Jar 3	Jar 4	Jar 5	Jar 6
Coagulant Dose (mg/L)	None	25	50	100	150	200	250
Turbidity (NTU)	0.37	1.03	0.57	0.90	2.61	2.16	3.05
Conductivity (mS/ $\mu$ m)	5.76	6.30	6.03	5.69	6.04	5.96	5.74
pH	9.23	8.64	7.86	7.33	6.05	4.86	4.70
TOC (mg/L)	120	115	116	113	114	114	115

The results show that the lower coagulant doses lower turbidity the most. Based on these results, a second set of coagulant experiments was performed. The range of dosages for this experiment was 20, 30, and 40 mg/L. For this second set, Sample #2 of raw Ball water was used

and three jar tests were run for each coagulant. 400mL again was the jar test size for each trial and results were evaluated based on the same four parameters. Parameters were again tested after flocculation, settling, and 6µm filtration. Results can be seen in Table 4.3.:

*Table 4.3: Iron and Alum Coagulant Results – Set 2, Single Tests from Water Sample #2*

Parameter	Blank	Jar 1	Jar 2	Jar 3	Jar 4	Jar 5	Jar 6
Coagulant Type and Dose (mg/L)	None	Fe 20	Fe 30	Fe 40	Al 20	Al 30	Al 40
Turbidity (NTU)	0.40	1.11	1.84	2.20	0.57	0.39	0.46
Conductivity (mS/µm)	6.01	6.03	5.98	6.04	6.01	6.00	5.99
pH	9.54	7.74	7.32	7.04	8.93	8.53	8.15
TOC (mg/L)	116	116	115	116	117	117	118

From the two sets of chemical coagulant trials, it can be observed that an iron coagulant dosage of 20 mg/L and an alum coagulant dosage of 30 mg/L are optimal based on turbidity reduction.

#### **4.1.2. Electrocoagulation – Procedures and Results**

Electrocoagulation was the alternative coagulation process tested. Electrocoagulation bench scale testing was modelled after WaterTectonics<sup>TM</sup> electrocoagulation testing process. Like chemical coagulants, electrocoagulation was initially tested using jar tests. These jar tests were performed at WaterTectonics lab in Everett, WA, and their results can be found in Appendix A. These jar tests were performed by inserting two plates of iron, aluminum, or one of each into a jar of Ball water and administering a set amperage for a set amount of time. The amount of time and amps altered the dosage for the electrocoagulation trial. WaterTectonics standardizes dosages 1x at different levels such as 1x, 2x, 3x. A 1x dose for a 400mL jar test is approximately 1 amp for 13 seconds. A 2x dose is double the dosage of a 1x electrocoagulation dosage; this can be done by either doubling the amperage, time, or a combination of the two.



Dosage calculations could be fine tuned using WaterTectonics Theoretical EC Calculator spreadsheet (Appendix A).

After coagulation was administered, jars allowed to flocculate for 15 minutes, and then sludge was settled out for approximately 30 minutes. Treated water was filtered through an 8 $\mu$  filter followed by a 0.22 $\mu$ m filter. Turbidity, conductivity, and pH were then measured. Overall, the jar tests for electrocoagulation provided similar results for varying dosages and type of cathodes/anodes applied. Because of these similarities, jar tests were typically not performed at CSU.

Instead large, flow through electrocoagulation cells were applied. The coagulation cell and bench scale control unit used by Colorado State University are shown below. Both the cell and the bench scale control unit were donated to CSU by WaterTectonics™.



Figure 4.1: EC Control Unit



Figure 4.2: EC Cell

This large, flow through unit could be adjusted for flow rate, amperage, and polarity within the electrocoagulation cell. Reducing the dosage could be done by either lowering the flow rate or decreasing the amps administered. A 1x dose on the flow through unit consists of 1 amp for a 0.5 GPM flowrate. During testing at WaterTectonics lab, the large electrocoagulation unit was also operated in a “batch” process similar to the jar tests at a 1x dose. The sludge was

settled overnight and the results can be seen in the table below compared to the raw sample before electrocoagulation.

*Table 4.4: Initial Large EC Trial - 1x Dose, Single Tests from Water Samples #3 and #4*

Parameter	Raw Ball Water	After EC and Settling (No filtration)
Turbidity (NTU)	34.9	12.6
Conductivity (mS/ $\mu$ m)	6.57	6.52
pH	9.66	9.97
TOC (mg/L)	104	107

Later testing of the large electrocoagulation unit produced similar results when conducted at CSU labs. These results are included later in Phase II as part of the full treatment train.

#### **4.1.3. Coagulation – Discussion of Results**

In general, all coagulation techniques tested performed well in settling out sludge and removing suspended solids. However, there were some characteristics and trends that were noticeable. Firstly, chemical coagulants were detrimental to water quality if used in excess. At levels above 50 mg/L for iron and 100 mg/L for alum, turbidity of the water actually increased instead of decreased. The relatively small amount of suspended solids in the effluent water did not require large amounts of coagulant; extra coagulant simply polluted the water. Electrocoagulation reduced turbidity to similar degrees as chemical coagulation and never was detrimental to turbidity if applied in excess. 1x, 2x, and 3x dosages for both iron and aluminum electrocoagulation cells performed well. Electrocoagulation required higher settling times, however, and overnight settling was often performed.

In addition, chemical coagulants reduced the pH of the Ball water in correlation to the amount of coagulant added. Iron coagulant lowered pH of the water more significantly, but both coagulants took aqueous forms,  $\text{Fe}(\text{OH})_3$  and  $\text{Al}(\text{OH})_3$ , respectively. These aqueous forms

released free hydrogen cations into the water, thereby lowering the pH. Figure 4.3 shows how pH was reduced even in the second, more precise, chemical coagulant trial. Alum lowers pH less significantly, but just as consistently.

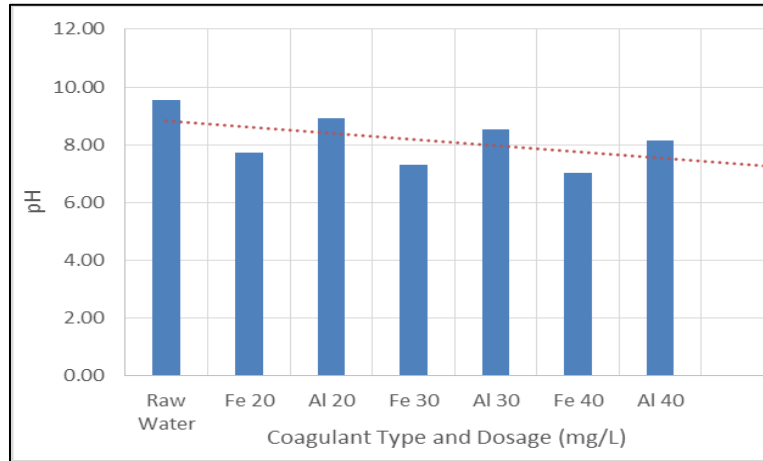


Figure 4.3: Chemical Coagulants – pH, Single tests from Water Sample #2

Electrocoagulation did not reduce pH to the same degree or as consistently as chemical coagulants. In jar tests performed at WaterTectonics, raw Ball water pH started at 10.43 and did not drop to any less than 10.02 no matter the dosage applied.

Conductivity and TOC were generally unaffected by any type of coagulation process. However, electrocoagulation, when combined with ultrafiltration in a later step, showed a slight advantage in TOC reduction. This slight reduction can be seen in Figure 4.4 below.

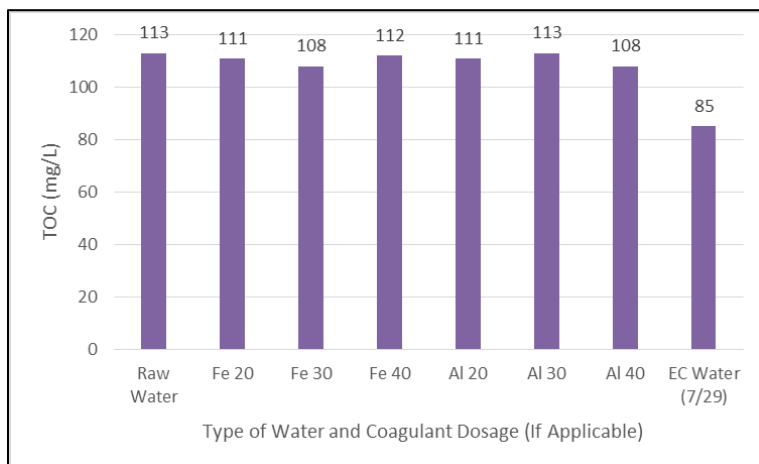


Figure 4.4: Electrocoagulation and Ultrafiltration - TOC Reduction, Single tests from Water Sample #2

Other than the main four parameters, sludge production in terms of mass and volume was also important to Ball Corporation. This was an important parameter since sludge disposal is a large contributor to waste disposal and the current filter press at the Fairfield plant was at maximum capacity. Here, electrocoagulation outperformed both chemical coagulants. Again, 400 mL jar tests were performed for five different coagulation scenarios: 20 mg/L iron, 30 mg/L alum, and 1x, 2x, and 3x dosages for iron electrocoagulation. After flocculation and before settling, 100 mL of each were sampled and filtered to acquire total solids concentration. The results in relation to mass per volume can be seen in Figure 4.5 below. Volumes of sludge produced by each coagulation process could not be accurately measured because they were too small per 100mL of sample. However, the alum coagulant followed by iron, the other chemical coagulant, had noticeably larger volumes of sludge when observed in graduated cylinders. Alum coagulant was approximately 3mL of volume per 100mL while the other sludges were about 1mL.

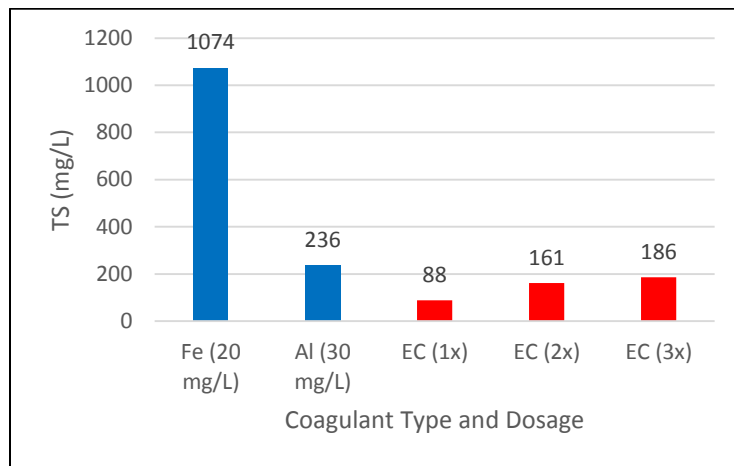


Figure 4.5: Sludge Production - Total Solids Comparison (mg/L), Single tests from Water Sample #6

In summary, electrocoagulation was more beneficial to Ball Corporation than chemical coagulants in some areas due to its lack of chemical additives, slightly better reduction in TOC, ease of use, and minimal sludge management. However, its drawbacks included longer settling

time and potentially higher costs. Electrocoagulation also better maintains the influent pH of the water unlike the chemical coagulants which significantly reduce pH. Based on the knowledge and experience with electrocoagulation from both CSU and WaterTectonics, Ball Corporation's desire to remove chemical additives, and good bench scale test results, electrocoagulation was determined to be the best coagulation and pretreatment option going forward with the rest of the treatment design.

## **4.2. Ultrafiltration**

The second treatment technology evaluated was filtration, specifically ultrafiltration. As described in the Phase I report, the primary purpose of ultrafiltration is to remove all suspended solids in water and thereby reduce turbidity down to essentially zero. Ultrafiltration utilizes size exclusion to remove suspended solids by preventing them from passing through fine pore sizes ranging from 0.03 to 1 $\mu$ m in diameter. In CSU's testing, small ultrafiltration devices were initially tested and scaled up once proven successful. In general, all ultrafiltration processes tested by CSU removed almost 100% of the waste stream's turbidity and were an effective pretreatment for reverse osmosis. This section of Phase II will first describe the small scale ultrafiltration procedures and results followed by the large scale procedures and results. After both results are presented, they will be briefly discussed.

### **4.2.1. Small Scale Ultrafiltration – Procedures and Results**

Multiple levels of filtration and ultrafiltration were conducted in order to determine the pore size required to filter out suspended solids and TOC if possible. Filter pore sizes of 8 $\mu$ m, 6 $\mu$ m, 1.5 $\mu$ m, 0.2 $\mu$ m, 0.1 $\mu$ m, 50 kDa, and 1 kDa were all tested to some degree on a small scale. As much treated water from the coagulation tests was poured off the top of the test jars as possible to be used in filtration procedures. The first set of coagulation results were all run

through 6 $\mu$ m, 1.5 $\mu$ m, and 0.2 $\mu$ m filters and tested for turbidity, pH, conductivity, and TOC after each filtration step. 6 $\mu$ m and 1.5 $\mu$ m filtrations were conducted using vacuum filtration. Vacuum filtration units used are pictured in Figure 4.6. 0.2 $\mu$ m filtrations were completed through syringe filters and are shown in Figure 4.7. The series of results from the lowest dosage trials (25 mg/L) for iron and alum coagulation can be seen in the tables below. A complete series of results for 6 $\mu$ m, 1.5 $\mu$ m, and 0.2 $\mu$ m filters from each level of coagulant dosage (50 mg/L, 100 mg/L, 150 mg/L, etc) can be found in Appendix B.

Table 4.5: Iron Coagulant Progression - Set 1, Single Tests from Water Sample #1

Parameter	After 10 min Settling	6 $\mu$ m	1.5 $\mu$ m	0.2 $\mu$ m
Turbidity (NTU)	1.72	1.03	2.00	0.16
Conductivity (mS/ $\mu$ m)	5.70	5.67	5.12	5.13
pH	7.98	7.45	7.74	8.09
TOC (mg/L)	116	115	117	92

Table 4.6: Alum Coagulant Progression - Set 1, Single Tests from Water Sample #1

Parameter	After 10 min of Settling	6 $\mu$ m	1.5 $\mu$ m	0.2 $\mu$ m
Turbidity (NTU)	0.76	1.03	1.14	0.10
Conductivity (mS/ $\mu$ m)	5.85	6.30	6.06	6.32
pH	8.66	8.64	8.50	8.31
TOC (mg/L)	118	115	119	118



Figure 4.6: Vacuum Filtration - 6 $\mu$ m, 1.5 $\mu$ m



Figure 4.7: Syringe Filter - 0.2 $\mu$ m

After these initial filtrations, the 25 mg/L alum sample was filtered through 0.1µm and 1 kDa. 0.1µm filtration was conducted through another syringe filter. The 1 kDa filtration process was performed by using an Amicon™ stirred cell filtration unit. This bench filtration option requires compressed air to force contaminated water through a flat filtration membrane at the bottom of the unit. The 1 kDa filter means that only atomic mass unit equal or less than 1,000 daltons. This is approximatedly equivalent to 0.0013µm; easily the smallest pore size evaluated in this thesis. The results from these two filtration steps compared to Ball water without coagulation are shown on the next page in Table 4.7.

*Table 4.7: Stirred Cell Results - Set 1, Single Tests from Water Sample #1*

Parameter	Alum -25 mg/L		Raw Ball Water	
	0.1 µm	1 kDa	0.1 µm	1 kDa
Turbidity (NTU)	0	0	0	0
Conductivity (mS/µm)	6.01	5.61	6.12	5.23
pH	8.47	8.28	9.07	9.06
TOC (mg/L)	117	96	125	87

The second set of chemical coagulant trials was also run through ultrafiltration processes. In this set, 6µm and 50kDa (0.04 µm) filtration were applied while intermediate filtration steps of 1.5µm and 0.2µm were skipped. The 6µm filtration was again conducted using vacuum filtration while the 50kDa filtration used the Amicon filtration cell. This 50kDa filtration step most accurately simulated the large scale ultrafiltration process and typical ultrafiltration pore sizes. Ultrafiltration results from this set of tests can be seen below. These results also include water run through electrocoagulation while at WaterTectonics lab and raw Ball water filtered through 6µm and 50kDa only.

Table 4.8: After 6µm and 50kDa Ultrafiltration – Set 2, Single Tests from Water Sample #2

Parameter	Blank	Jar 1	Jar 2	Jar 3	Jar 4	Jar 5	Jar 6	Jar 7
Coagulant Type and Dose (mg/L)	Raw Water	Fe 20	Fe 30	Fe 40	Al 20	Al 30	Al 40	EC 1x (7/29)
Turbidity (NTU)	0.07	0.10	0.08	0.07	0.07	0.09	0.10	0.38
Conductivity (mS/µm)	5.95	5.96	6.01	6.09	6.04	6.04	6.06	6.09
pH	9.48	7.72	7.35	7.02	8.80	8.37	7.97	8.84
TOC (mg/L)	113	111	108	112	111	113	108	85

#### 4.2.2. Large Scale Ultrafiltration

After running successful results on small scale filtration and ultrafiltration membranes, larger ultrafiltration tests were approved and tested. The large scale hollow fiber ultrafiltration membrane tested was designed by Mann+Hummel™ and donated to CSU by WaterTectonics. This membrane had a pore size of 0.05µm, very similar to the 50kDa stirred cell pore size (0.04µm). The max flow rate allowed by the large unit was 0.5 GPM, it operated in dead end mode filtration, and could function over a large range for pH and turbidity. Operation of this large ultrafiltration unit involved pumping water into the ultrafiltration casing. The chamber would then fill up with untreated water until pressure was great enough for the water to be forced through and the hollow fiber membranes and filtered. Treated water would then flow up the hollow fibers and out the other end of the casing. Figure 4.2.4 on the following page shows the hollow fiber membrane in the lab and diagrams its operation step by step.



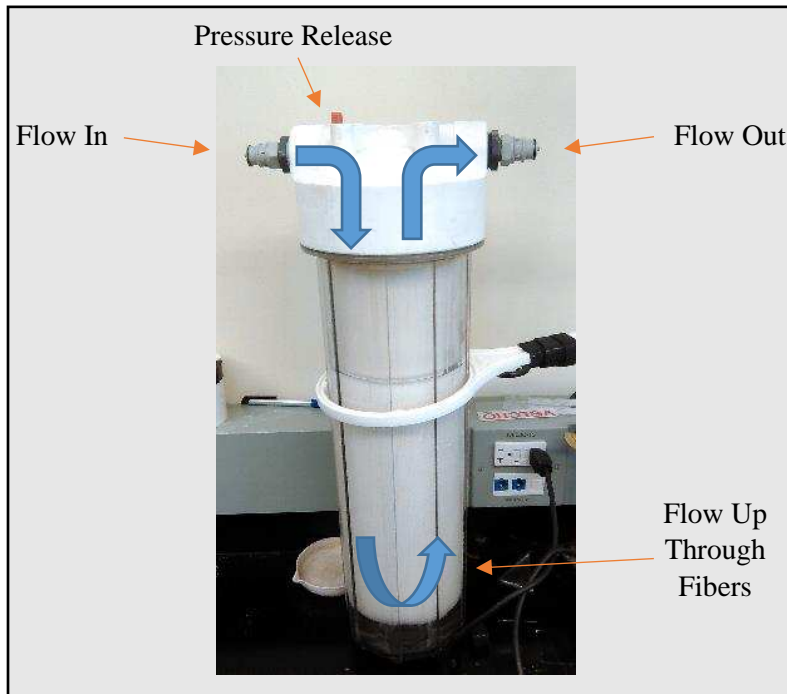


Figure 4.8: Large UF Unit and Diagram

The large scale UF membrane reduced total suspended solids and turbidity as effectively as small scale operations. Below in Table 4.9 are results from after large scale ultrafiltration from the WaterTectonics lab in Washington and the CSU lab, and with and without electrocoagulation. All three sets of results were the tested from similar, but separate raw water samples. The large scale ultrafiltration unit was always paired with large scale electrocoagulation or no coagulation at all, never chemical coagulation. Electrocoagulation could be easily done for multiple liters, but chemical coagulation required more coagulant than easily available and was deemed unnecessary after the small scale results.

Table 4.9: Large Scale UF Unit Results, Single tests from Water Samples #3+4, #8, and #10 Respectively

Parameter	WaterTectonics - 1x EC Dose	CSU Lab - 1x EC Dose	CSU Lab - Raw Ball Water
Turbidity (NTU)	0.38	0.13	0.93
Conductivity (mS/ $\mu$ m)	6.09	6.18	5.44
pH	8.84	7.21	9.58
TOC (mg/L)	85	78.99	96.7

### 4.2.3. Ultrafiltration – Discussion of Results

The main conclusion from filtration and ultrafiltration testing is that turbidity and suspended solids can be completely removed from the Ball water, whether coagulated and decanted beforehand or filtered directly. Though turbidity tests show some fluctuation between coagulation results and after different filter pore sizes, as long as turbidity is measured below 1 NTU it can be assumed that all suspended solids have been removed. The precision of the turbidimeter both at the CSU lab and especially at WaterTectonics were not designed to measure turbidities with complete precision at such low turbidities. Therefore, all turbidities below 1 NTU can be seen as effectively equivalent.

Based on this knowledge, it is interesting to examine the results from Tables 4.5 and 4.6 more closely. Below are the turbidity results from these alum and ferric progressions:

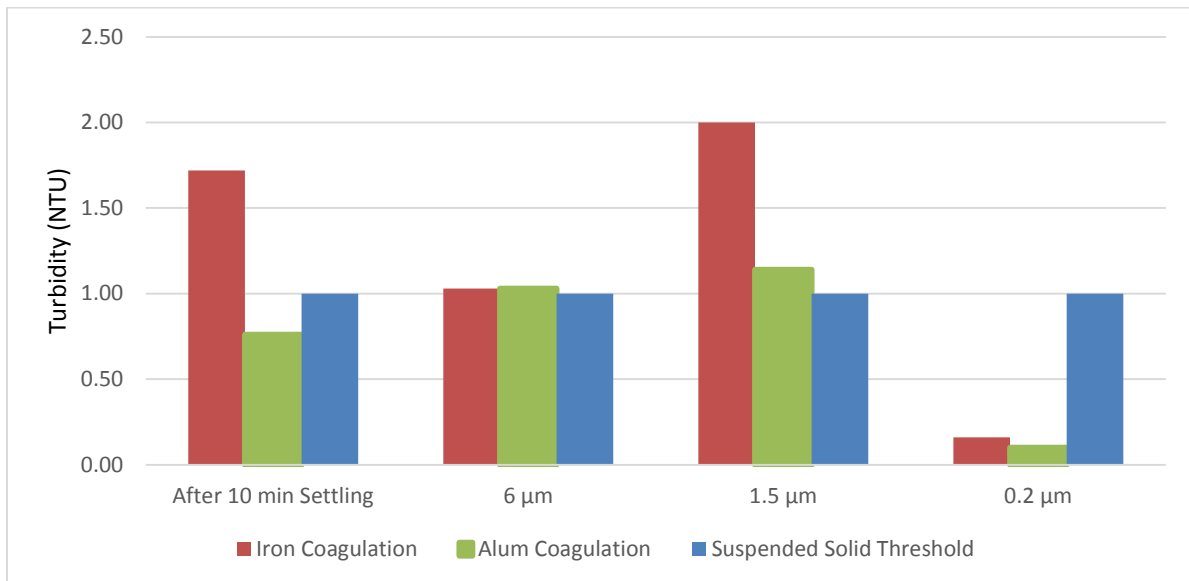


Figure 4.9: Chemical Coagulant Turbidity Progression – Set 1, 25 mg/L Doses, Single Tests from Water Sample #1

Turbidity from these initial sets of treatment decreases significantly and below the 1 NTU “threshold” only after 0.2µm pore size ultrafiltration treatment. This indicated that the remaining suspended solids after flocculation and separation are smaller than what can be filtered out with

the 6 $\mu$ m and 1.5 $\mu$ m pore sized filtration. The remaining particles in the water after coagulation and decanting are therefore in the 1.5-0.2 $\mu$ m range. Based on this information, it makes sense that both the small scale and large scale ultrafiltration procedures with pore sizes below 0.2 $\mu$ m removed essentially 100% of all turbidity.

Conductivity and pH were not expected to vary based on the ultrafiltration technique. As expected, both parameters held steady regardless of the pore size due to their dissolved nature. Size exclusion has no effect on either of the two parameters. Dissolved metals and anions, which make up conductivity, were identified by sending samples to ALS Laboratory. The majority of dissolved substances in ultrafiltration effluent were sulfate and sodium ions. These ions likely were byproducts from drastic alterations to pH undertaken by the washer water. The full list of dissolve substances tested can be found in Appendix B. Conductivity and pH progressions for both chemical coagulants and raw water filtered over a range of coagulant doses are shown in the figures below.

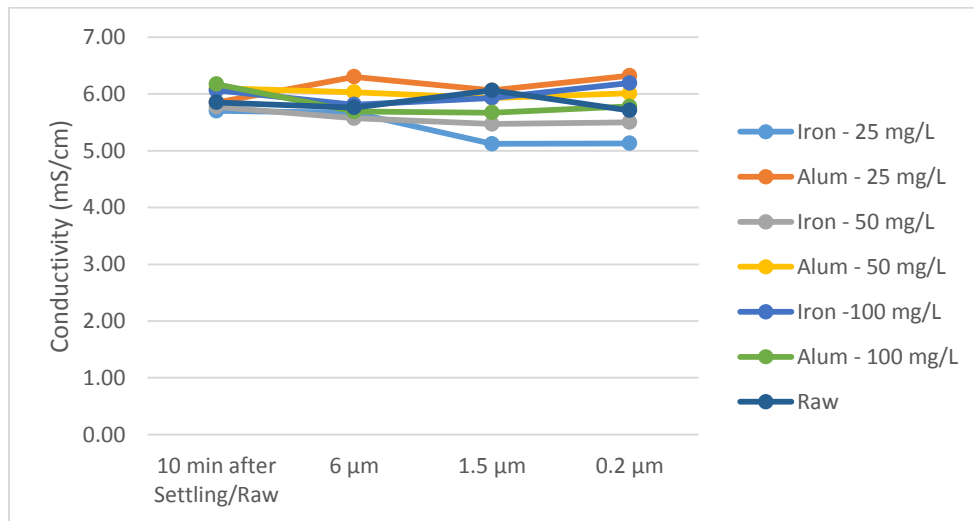


Figure 4.10: Conductivity Progression - Set 1, Single Tests from Water Sample #1

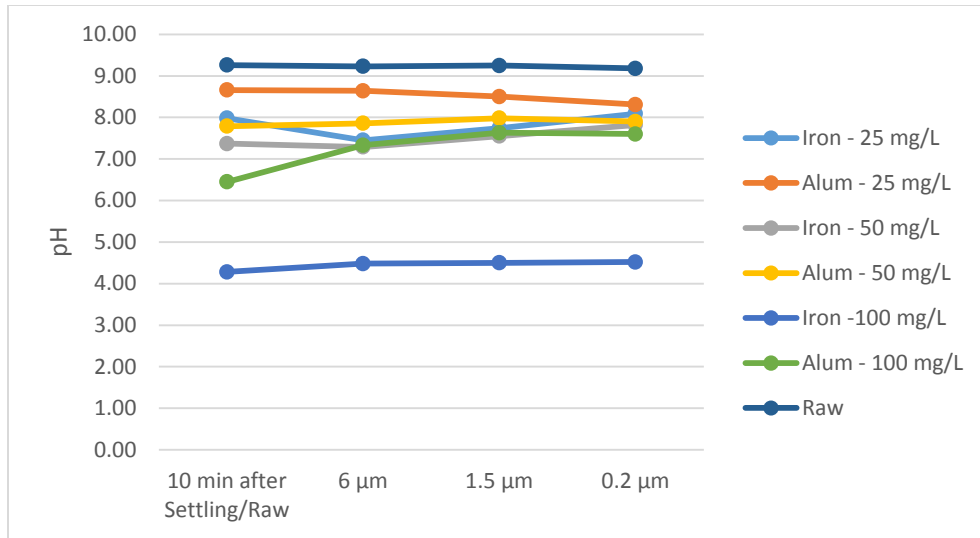


Figure 4.11: pH Progression - Set 1, Single Tests from Water Sample #1

TOC was hoped to be able to be reduced significantly by ultrafiltration as well. However, much of the TOC in the effluent water is present as dissolved organic carbon (DOC) and cannot be removed through ultrafiltration. Surfactants added in the can washing processes were likely the main contributor to high DOC levels. Because of this, only the finest ultrafiltration trial – the 1kDa (0.0013µm) pore size – showed any sign of significant TOC removal. In this trial, raw water TOC was reduced from 125 to 87 mg/L and the optimum dosage for alum sample was reduced from 117 to 96 mg/L. This pore size, however, is not typically used for any large scale filtration operation. In addition, TOC was still not reduced significantly enough to ensure prevention of organic membrane fouling for the final treatment step, reverse osmosis. TOC levels needed to be in the range of 0-10 mg/L before reverse osmosis could be applied.

All of the discussed ultrafiltration technologies tested were dead end filtration operations. A crossflow unit was also briefly tested to examine any potential difference it might have in comparison to the dead end ultrafiltration process. A disposable Sartorius™ Vivaflow 50 crossflow cassette membrane (pore size 50kDa) was tested and found to produce matching

results compared to dead end operation treatment tests. Expected removal rates for suspended solids were concluded to be similar for dead end flow operations and cross flow operations.

### **4.3. Granular Activated Carbon**

High DOC levels would quickly damage the delicate reverse osmosis membranes through irreversible organic fouling if left untreated. Therefore, an additional treatment step was necessary to specifically target DOC. For this reason, granular activated carbon was introduced as a treatment process and tested. Granular activated carbon (GAC) is a form of charcoal physically altered to have small, low volume pores that greatly increase the surface area of the substance. GAC is able to remove DOC through adsorption of the organic compound to its large surface area. Once the GAC surface area is saturated with DOC and adsorption becomes minimal, activated carbon can be regenerated or disposed of and replaced. This section of Phase II will first describe isotherm creation which was initially tested to prove GAC effectiveness and then large scale GAC column procedures and results. After both sets of procedure and results are presented, they will be briefly discussed.

#### **4.3.1. GAC – Isotherms and Small Scale Testing**

The first step of GAC testing involved the determination of the optimal contact time and GAC dosage with jar tests. Ultrafiltered water (50 kDa) from the second set of coagulation tests was used. Only optimal doses of alum and iron coagulant were used from this set; 30 mg/L for alum and 20 mg/L for iron coagulant. With this sample water, the first test was to determine optimal contact time. In this procedure, equal ratios of grams of GAC to mL of sample water were allowed to mix in jar tests for varying amounts of time. The ratio of grams of GAC to mL of sample water was 1:250. Time steps tested were 10, 20, 30, 60, 90, and 120 minutes. Starting TOC concentrations for both alum and iron coagulated sample waters was 111 mg/L. Optimal

contact time was expected to occur when GAC was saturated and removal rate for TOC plateaued. Figure 4.12 below shows the percent removal rates from the optimal contact time test.

A TOC concentration table of concentrations in mg/L can be found in Appendix C.

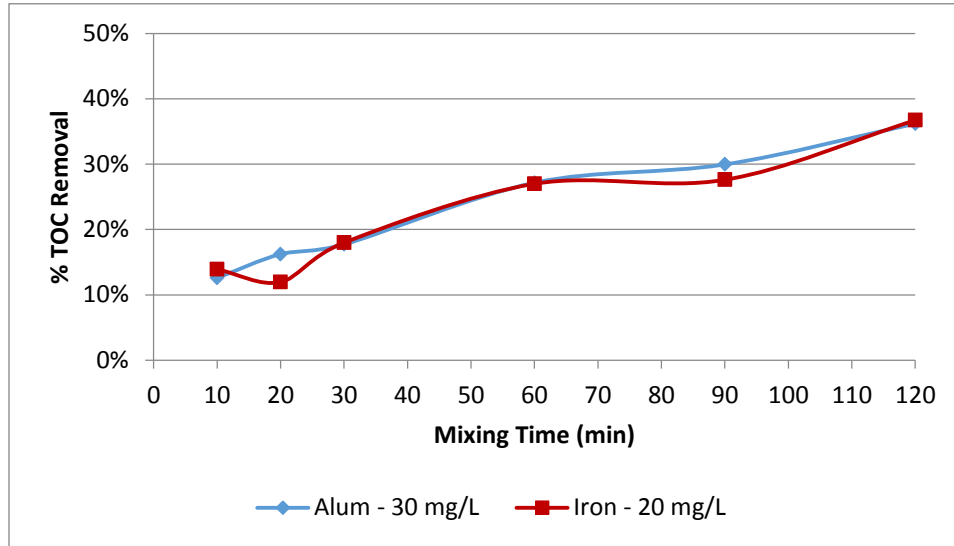


Figure 4.12: Optimal Contact Time Results, Single Tests from Water Sample #5

After the optimal contact time test, the optimal dosage test was conducted by fixing contact time and varying GAC doses. Ideally, the fixed time was supposed to be the optimal contact time, but since the optimal contact time test never reached a plateau or limit to GAC adsorption, 20 minutes of mixing was selected. 20 minutes was selected for this test because it was a feasible amount of time, not too long like 2 hours, yet still allowed for plenty of contact between the sample and GAC. Sample water from electrocoagulation (1x dose) and the large unit ultrafiltration process was also tested in this optimal dosage test. Sample waters for the optimal dosage test had the following characteristics as shown in Table 4.10 below:

Table 4.10: GAC Optimal Dose Test - Initial Characteristics, Single Tests from Samples #5, #6, and #3+4 Respectively

Parameters	Iron - 20 mg/L	Alum - 30 mg/L	EC (1x)
Turbidity (NTU)	0.56	0.92	0.38
Conductivity (mS/μm)	5.84	5.75	6.09
pH	9.67	9.70	8.84
TOC (mg/L)	102	105	85

100 mL of each sample were added to six jars each. In each jar, GAC amounts of 0.4, 1, 2, 3, 5, and 8 grams were added to examine the difference in TOC removal from a variety of doses. Jars were then mixed for a total of 20 minutes (10 min at 75 RPM, followed by 10 min at 50 RPM), filtered to remove GAC, and tested for TOC and other parameters. Tables 4.11-13 show the results for each sample below.

*Table 4.11: Optimal Dose Results - Alum 30 mg/L, Single Tests from Water Samples #5 and 6*

GAC Dosage (g)	TOC (mg/L)	pH	Conductivity (mS/cm)	Turbidity (NTU)
0.4	85	9.65	5.76	1.05
1	60	9.77	5.90	0.97
2	39	9.89	5.88	0.92
3	28	10.02	5.95	1.05
5	20	10.11	5.97	1.20
8	14	10.22	6.05	0.84

*Table 4.12: Optimal Dose Results - Iron 20 mg/L, Single Tests from Water Samples #5 and 6*

GAC Dosage (g)	TOC (mg/L)	pH	Conductivity (mS/cm)	Turbidity (NTU)
0.4	87.71	9.60	5.85	1.20
1	64.77	9.72	5.92	1.13
2	41.56	9.84	5.98	1.19
3	30.14	9.96	5.97	1.19
5	20.21	10.10	6.03	1.20
8	15.04	10.17	6.12	0.98

*Table 4.13: Optimal Dose Results - EC (1x), Single Tests from Water Samples #5 and 6*

GAC Dosage (g)	TOC (mg/L)	pH	Conductivity (mS/cm)	Turbidity (NTU)
0.4	70.64	8.65	6.11	1.77
1	49.23	8.98	6.13	1.05
2	34.60	9.16	6.19	0.89
3	21.06	9.41	6.26	0.53
5	10.77	9.66	6.32	0.45
8	5.06	9.84	6.43	0.29

Small scale GAC column testing was conducted after the initial jar tests. GAC columns better simulated industrial GAC filtration and could be tested for breakthrough analysis. The small GAC column was 2.5cm in diameter and 0.61m in length. It was filled with 30 grams of GAC and initially filtered with 75 mL of DI water to remove loose ash and sediment. Sample water from electrocoagulation and large unit ultrafiltration was added to the top of the column at a rate of 20 mL/min and allowed to filter through the saturated column. Once 75 mL of DI water was collected, testing of the treatment process began. Figure 4.13 shows the results from the small scale TOC exhaustion test and Figure 4.14 shows a picture of the small scale column. The table of results can be found in Appendix C.

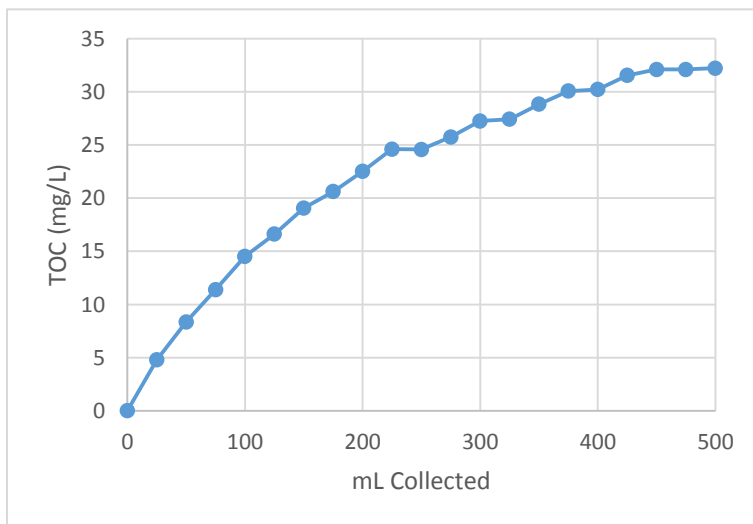


Figure 4.13: GAC Exhaustion Test - Small Column, WS #5 and 6



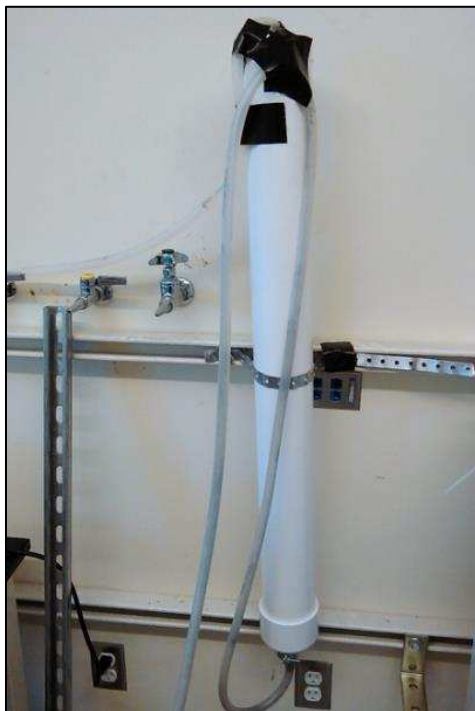
Figure 4.14: 1" Diameter Column

#### 4.3.2. GAC – Large Scale Testing and Results

After seeing effective results from small scale testing, large scale GAC column testing was conducted. A 7.62cm in diameter PVC pipe with a 1m length was mounted to hold 2800mL of GAC (~540g). Before the GAC was added, a plastic mesh and pebbles were placed at the bottom of the cylinder to hold as much GAC as possible in place. The GAC was then added and flushed with DI water to remove as much loose ash as possible. Sample water was added to the



column at rates between 70-100mL/min. Like the small column, tubing connecting the bottom of the column to the final outlet was raised and bent to keep the column full and the GAC saturated with sample water. Below in Figure 4.15 is the large GAC column.



*Figure 4.15: 3" Diameter GAC Column*

Water run through the large GAC column never exceeded 6 mg/L of TOC and most test results showed a non-detectable level of TOC. Even after treating over 40 gallons of water, breakthrough was never reached on the large GAC columns and the GAC never had to be regenerated or replaced. The large GAC column procedure was used to treat water for the final treatment trains.

#### **4.3.3. GAC – Discussion of Results**

Granular activated carbon was shown to be very effective at eliminating the dissolved organic carbon present in the Ball water. Surfactants and lubricants used in the can making process were the likely sources of the high TOC concentrations and their dissolvability made them impossible to remove with earlier treatment processes. The removal effectiveness of GAC

can be easily seen in Figure 4.15. This figure shows the results from the GAC optimal dose test graphically as a TOC removal percentage. The highest doses at 8 and 10 mg/L, where 86-98% removal is shown, would be the most representative of a fully operational, plug flow GAC column. It should also be noted that electrocoagulated water had the highest removal percentage at almost 100%. The electrocoagulated sample was also the only one to bring TOC concentration below the goal of 10 mg/L.

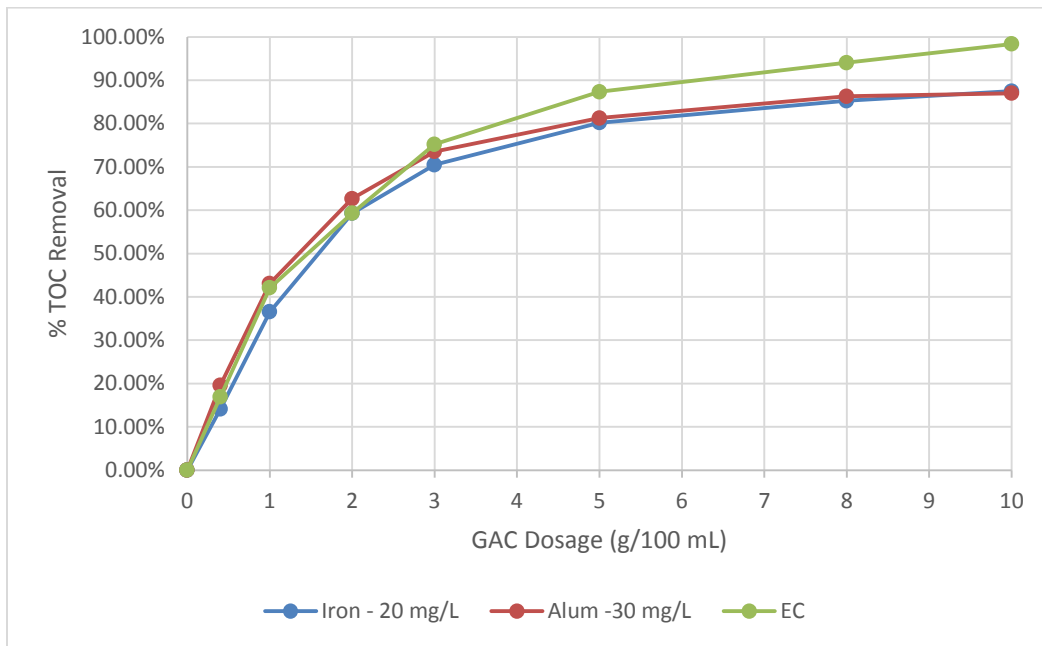


Figure 4.16: GAC - Dosage vs. % TOC Removal, Single Test from Water Samples #5 and 6

Besides elimination of TOC, granular activated carbon also showed varying effects on pH and conductivity. In the jar tests, pH and conductivity consistently both increased as the GAC dose was increased. These results are shown in Figures 4.16 and 4.17 on the following page. However, in the large scale column treatment processes, conductivity and pH actually decreased slightly after GAC treatment. This is likely due to small amounts of dilution with DI water occurring within the GAC column and very small amounts of GAC running off into the treated water. These potential errors in the large GAC column testing were not significant and did not affect the final results.

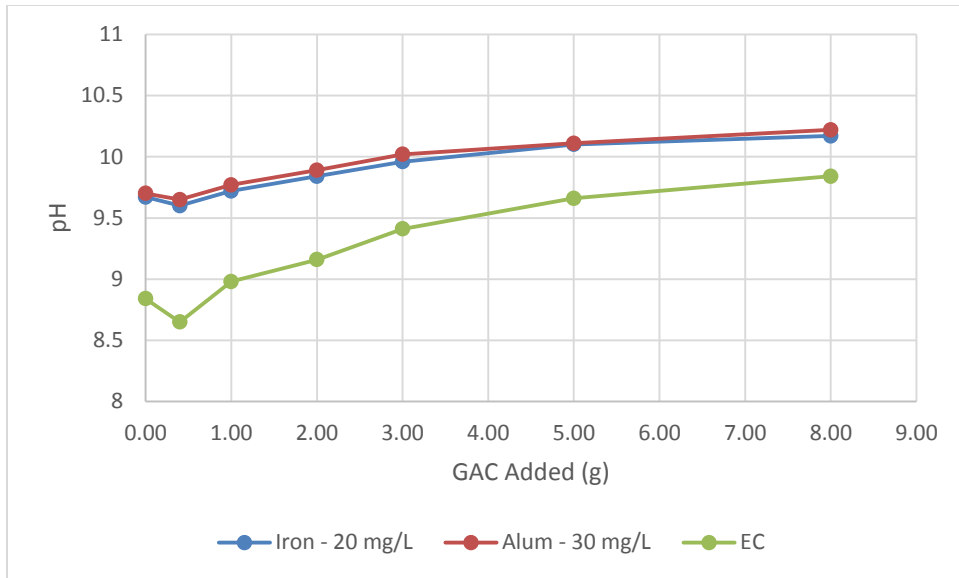


Figure 4.17: GAC Jar Tests - pH vs. Dose, Single Tests from Water Samples #5 and 6

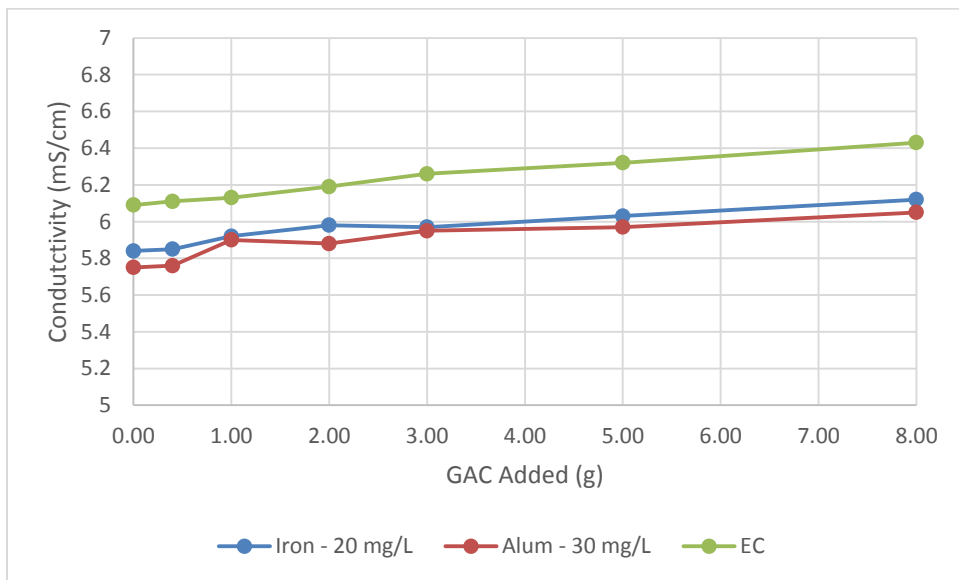


Figure 4.18: GAC Jar Tests – Conductivity vs. Dose, Single Tests from Water Samples #5 and 6

No changes in turbidity were observed from GAC treatment. GAC filtration units should never alter turbidity or suspended solids concentrations as long as granular activated carbon is not allowed to runoff in the filtered water.

Isotherm analysis was also conducted on for GAC treatment of Ball water. This data can be found in Appendix C.

#### **4.4. Reverse Osmosis**

The final process in the treatment train tested was reverse osmosis. Reverse osmosis is a water treatment process that depends on a semipermeable membrane and high pressures to overcome osmotic pressure in order to purify water. Reverse osmosis allowed CSU to focus on treatment of the final parameter still not removed: conductivity or total dissolved solids (TDS). The influent conductivity of about 6,000  $\mu\text{S}/\text{cm}$  needed to be treated to about 350  $\mu\text{S}/\text{cm}$  to match the conductivity of the City of Fairfield municipal water. Other options besides reverse osmosis were considered to treat dissolved solids such as distillation. However, based on the relatively low total dissolved solids concentration in the Ball Water waste stream ( $\sim 5,000$  mg/L), reverse osmosis was the best option. Reverse osmosis also allows for greater flexibility in terms of water quality and water quantity recycled or discharged to the POTW. This section of Phase II will first describe reverse osmosis modeling and small scale reverse osmosis procedures. Then large scale reverse osmosis testing will be similarly described. After both sets of procedures are presented, trends and results from both small and large scale testing will be shown and discussed.

##### **4.4.1. Reverse Osmosis – Modeling and Small Scale Testing**

Computer modeling using GE WinFlows™ software was the first step in optimizing the reverse osmosis process. Influent dissolved solids data and desired recovery rates were input into the program and optimum operating membranes, feed pressures, flow rates and recovered water qualities were output. Influent data input into WinFlows can be found in Appendix D. The recovery rate was set at 50% for all trials. WinFlows software suggested GE membranes and feed pressures for the influent Ball Water as seen in Table 4.14. In addition, CSU added two other membranes, a TriSep and a Toray, to analyze against the GE membranes. These

membranes could not be modeled with WinFlows since they are not GE products. Instead, feed pressures were determined based on suggestions from the manufacturers.

Table 4.14: Tested Membranes and Feed Pressures Based on Winflows Suggestions and Standard Operating Pressures

Membrane	Feed Pressure (psi)
GE AG8040F-400	127
GE AK8040F-400	95
GE CE8040F	236
TriSep ACM5	125
Toray 73AC	200

The WinFlows optimal membrane suggestion based on effluent TDS concentration, feed pressure, and influent water was the GE-AG membrane. Below is a screenshot from the GE-AG model. This screenshot shows the flow rates, recovery percentage, feed pressure, average flux, and estimated water quality output. A data input screenshot as well as GE-AK and GE-CE model screenshots can be found in Appendix D.

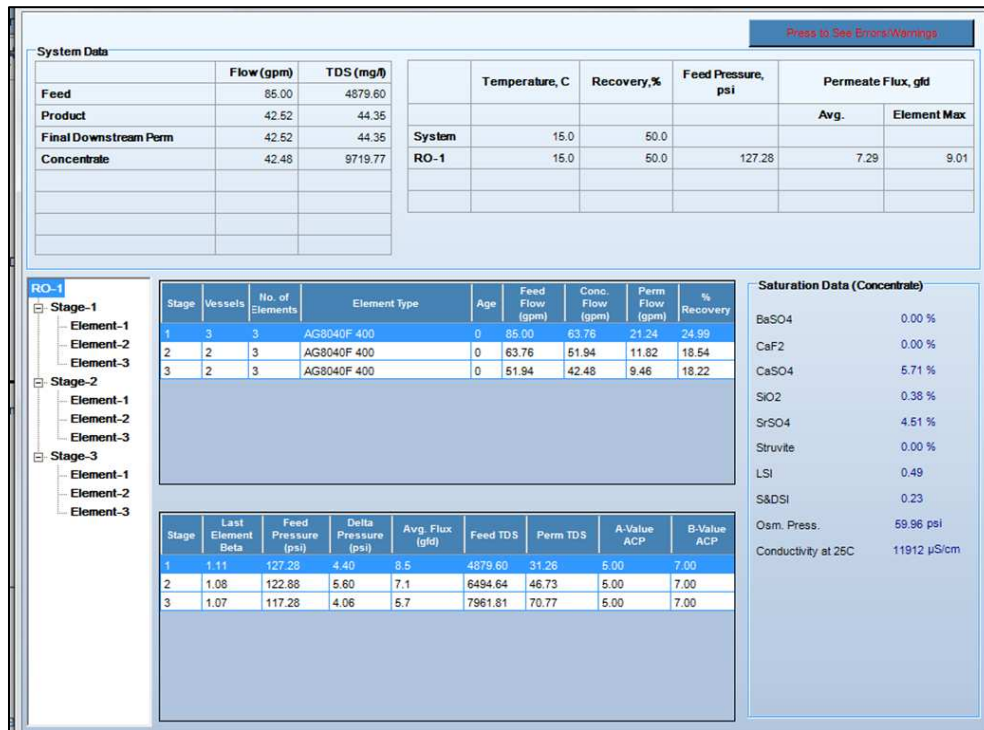


Figure 4.19: Reverse Osmosis – GE-AG WinFlow Results

Bench scale units exactly modeling the WinFlows models were not possible since each WinFlows model suggested a reverse osmosis process with a number of stages, but it was valuable in determining best operating pressure and alternate membranes. These models will also likely be valuable in full scale designs.

With the WinFlows models, small scale reverse osmosis processes were tested in the lab using a small, direct flow Sterlitech™ unit. This unit uses compressed air to force feed water directly through a 47 mm diameter reverse osmosis membrane. All five membranes were tested based off of suggested feed pressures. Two types of coagulants, iron at its optimal dose of 20 mg/L and 1x electrocoagulation were independent variables tested. In addition, water without GAC treatment and water with GAC treatment were tested to determine if any short term fouling would occur if TOC were not removed before reverse osmosis. A 50% recovery rate was also set for all tests. To do this, 50 mL of influent water was added to the unit and permeate was collected once 25 mL had passed through the membrane. Once 25 mL of both brine and permeate were collected, both were tested for total dissolved solids (TDS), conductivity, TOC, and pH. The flux over the course of each trial was also recorded by keeping track of the time until 25 mL of permeate was collected. The complete data tables from these trials can be found in Appendix D. In general, all membranes and all types of influent water produced adequate permeate water qualities.

#### **4.4.2. Reverse Osmosis – Large Scale Testing**

The large scale, cross flow unit was the second treatment test for reverse osmosis. This Sterlitech SEPA CF cell (Figure 4.20 on the next page) was able to test the same membranes at higher volumes and for longer durations. Unlike the small scale, direct flow unit, the SEPA cell operated in a cross flow fashion forcing water across the membrane instead of directly through it.

This allowed recirculation of the water. Like the smaller unit, the SEPA cell was set at specific feed pressures depending on the type of membrane. However, only the GE-AG membrane was tested using the SEPA cell so the pressure was always set at approximately 125 psi.



*Figure 4.20: Large Scale Reverse Osmosis - SEPA Cell*

The first test for the SEPA cell was designed to analyze fouling of the reverse osmosis membrane. Thirty liters of influent water treated using electrocoagulation, ultrafiltration, and granular activated carbon was pumped through the SEPA cell containing a GE-AG reverse osmosis membrane. This influent water had a starting conductivity of 6.01 mS/cm. The SEPA cell was run for 25 hours and the results from this fouling test can be seen in Table 4.4.2 on the following page. At the end of the 25 hours, 60% of the influent water was permeate at a conductivity of 0.13 mS/cm while the brine contained approximately 40% at a conductivity of 12.54 mS/cm. Feed, brine, and permeate samples were sent to ALS Laboratories to test for ion concentrations. The results on the following page show the recycle flow rate, or the rate at which water flowed not through the membrane, but back to the influent reservoir. The final column also shows how the influent pressure changed over time.

Table 4.15: Reverse Osmosis - 25 Hour Fouling Test, Single Test with Water Samples #7 and 8

Time:	Hours:	Recycle Flow Rate (GPM):	Pressure (psi):
9:00 A.M.	0	0.78	120
10:00 A.M.	1	0.80	125
12:00 P.M.	3	0.83	120
2:00 P.M.	5	0.82	140
4:00 P.M.	7	0.81	120
10:00 P.M.	13	0.85	125
8:00 A.M.	23	0.89	150
10:00 A.M.	25	0.89	150

After testing for fouling, CSU and WaterTectonics researchers analyzed the difference between two sets of treatment trains determined to be the most optimal for Ball Corporation. The first treatment train contained large scale electrocoagulation, ultrafiltration, granular activated carbon, and reverse osmosis processes. The second train skipped electrocoagulation and forced raw Ball water directly through the ultrafiltration step, followed by granular activated carbon and reverse osmosis. For this reverse osmosis trial, six liters of both Train 1 and Train 2 were pumped through the SEPA cell. Three liters of brine and permeate were collected to make the recovery ratio of 50% consistent with small scale tests. Both brine and permeate were tested for turbidity, TOC, conductivity, and pH. Reverse osmosis feed water, permeate, and brine samples were also sent to ALS Laboratories for specific ion concentrations. These results are presented and discussed in Section 4.5. Full Treatment Train Comparison.

#### 4.4.3. Reverse Osmosis – Results and Discussion

The small scale results show a number of significant trends. Firstly, all types of membranes with different prior coagulants and GAC treatments produced permeate water that very closely matches the municipal water TDS concentration. Figure 4.21 on the following page shows total dissolved concentrations for permeates from the small scale trials in relation to Fairfield’s municipal water TDS and TDS prior to reverse osmosis. It also shows each type of



membrane used, both type of coagulants (EC, Fe), and whether the feed water had GAC treatment or not.

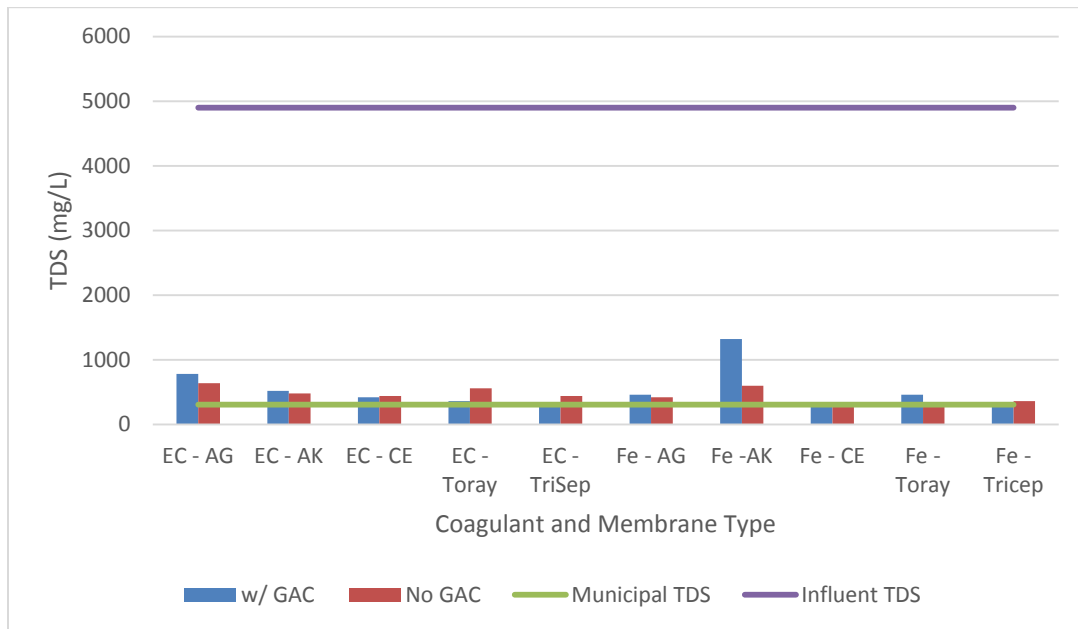


Figure 4.21: Small Scale Reverse Osmosis - TDS Comparison, Single Tests with Water Samples #2 and #6

Based on these TDS and corollary conductivity results, no membrane showed significant advantages over any other. Therefore, the membrane suggested as optimal by WinFlows, GE-AG, was determined to be the optimal membrane going forward. There were, however, noticeable differences in pH between coagulants used. Like in previous trials, ferric chloride produced overall greater pH values than electrocoagulation reverse osmosis trials. These differences can be seen in Appendix D. In addition to pH changes, the contrast between GAC treated and non-GAC treated water was also significant. Non-GAC treated water showed much greater concentrations of TOC in produced permeate and brine. Municipal water tested at 2 mg/L TOC, but permeate without GAC treatment consistently exceeded this concentration, regardless of the membrane or coagulant used. Figure 4.22 on the next page shows the permeate TOC results compared vs. the municipal water threshold.

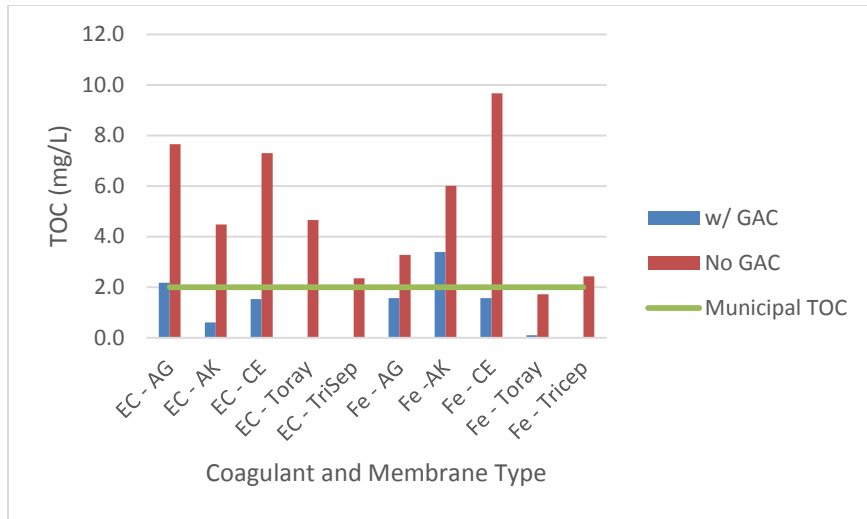


Figure 4.22: Small Scale Reverse Osmosis - Permeate TOC Comparison, Single Tests with Water Samples #2 and 6

In addition to this trend, which showed the importance of GAC treatment, was the difference in flux between GAC and non-GAC. GAC treated water consistently had a greater flux rate than non-GAC treated water. This is due to organic fouling caused by higher TOC concentrations in non-GAC treated water. Organic matter clogs the membrane and slows the flux, thus making a large scale reverse osmosis process less efficient and much more costly. Figure 4.23 below shows the flux results for all membranes tested. In addition, there is a consistent difference between water with GAC treatment and water without GAC treatment.

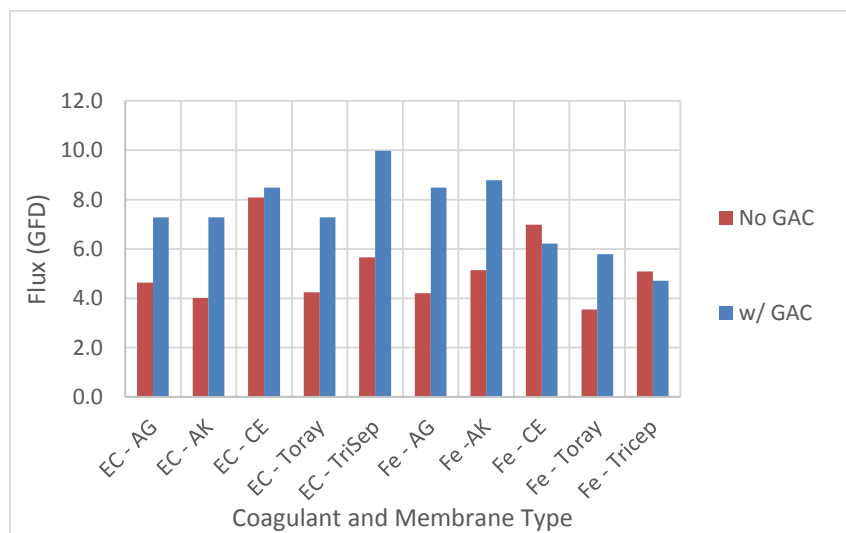


Figure 4.23: Small Scale Reverse Osmosis - Flux Comparison, Single Tests with Water Samples #2 and 6

Combining all these trends shows the importance of GAC treatment, the lasting difference coagulation treatments can have on a treatment process, and the similarity of reverse osmosis membranes. With the large scale reverse osmosis treatment, large enough water samples could be collected so that specific ion data could be gathered and compared. Feed, brine, and permeate data from the fouling test are shown in Table 4.16. Reverse osmosis was effective at removing salts on the pretreated Ball water (Table 4.16). Concentrations of all ions except chloride, sulfate, and sodium were removed down to non-detectable levels. In addition, the brine concentration reflects the 60:40 permeate to brine ratio by more than doubling the ion concentrations of the feed water. Even with these doubled concentrations, none of the Fairfield water discharged standards for wastewater are exceeded. However, this is mostly due to the lack of overlap between contaminants regulated by Fairfield POTW and contaminants found at detectable concentrations in Ball wastewater.

*Table 4.16: Reverse Osmosis Fouling Trial – Ion Results, Single Test with Water Samples #7+8*

Parameters:	Feed to RO	Brine (~40%)	Permeate (~60%)
Bicarbonate as CaCO <sub>3</sub> (mg/L)	170	330	ND
Total Alkalinity as CaCO <sub>3</sub> (mg/L)	210	340	ND
Chloride (mg/L)	95	240	4
Sulfate (mg/L)	3200	7900	25
Barium (mg/L)	ND	0.16	ND
Calcium (mg/L)	13	47	ND
Potassium (mg/L)	82	190	ND
Magnesium (mg/L)	14	36	ND
Sodium (mg/L)	1500	3200	15
Silicon as SiO <sub>2</sub> (mg/L)	1.6	3.4	ND
Silicon (mg/L)	0.73	1.6	ND
Strontium (mg/L)	0.27	0.95	ND

#### **4.5. Full Treatment Train Comparison**

After analyzing these different treatment processes, weighing costs and feasibility, and considering the described bench scale results, two final treatment trains appeared to be the best current options. The two options are as follows:

1. Electrocoagulation followed by settling basin or DAF, ultrafiltration, GAC treatment, and reverse osmosis, or
2. Removing the electrocoagulation step and going straight to ultrafiltration, GAC treatment, and reverse osmosis

Both options have been tested by CSU and the results are shown in the following tables. The large electrocoagulation cell, large hollow fiber ultrafiltration membrane, and large GAC column were used as pretreatment steps before reverse osmosis. It should be noted that each train is based off of slightly different raw water samples (Samples #9 and 10). Train 1 (with electrocoagulation) has a lower starting conductivity than Train 2 for example. Both treatment trains have 50% recovery ratios. 6000mL of feed water was tested resulting in 3000mL of brine and 3000mL of permeate. Both treatment trains were tested with GE-AG membranes for the reverse osmosis process. Ion concentration results were tested by ALS Laboratories.

Table 4.17: Train 1 (With Electrocoagulation) – Results, Single Test from Water Sample #9

Parameters:	Raw Water	After EC and Settling	After Ultrafiltration	After GAC/Feed to RO	Brine	Permeate
Turbidity (NTU)	18.1	3.62	0.5	0.5	<1	<1
pH	9.65	7.56	7.44	6.92	7.05	8.3
Conductivity (mS/cm)	6.33	6.15	6.01	5.79	10.79	0.32
TOC (mg/L)	96.23	83.88	74.26	0	0	0
Bicarbonate as CaCO <sub>3</sub> (mg/L)	N/A	N/A	N/A	210	360	19
Carbonate as CaCO <sub>3</sub> (mg/L)	N/A	N/A	N/A	ND	39	ND
Total Alkalinity as CaCO <sub>3</sub> (mg/L)	N/A	N/A	N/A	210	400	19
Chloride (mg/L)	N/A	N/A	N/A	92	180	12
Sulfate (mg/L)	N/A	N/A	N/A	3200	6200	64
Barium (mg/L)	N/A	N/A	N/A	ND	ND	ND
Calcium (mg/L)	N/A	N/A	N/A	13	26	ND
Potassium (mg/L)	N/A	N/A	N/A	73	140	4.7
Magnesium (mg/L)	N/A	N/A	N/A	13	26	ND
Sodium (mg/L)	N/A	N/A	N/A	1400	2700	41
Silicon as SiO <sub>2</sub> (mg/L)	N/A	N/A	N/A	1.4	2.7	0.15
Silicon (mg/L)	N/A	N/A	N/A	0.64	1.3	0.071
Strontium (mg/L)	N/A	N/A	N/A	0.23	0.48	0.016

Table 4.18: Train 2 (No Electrocoagulation) – Results, Single Test from Water Sample #10

Parameters	Raw Water	After Ultrafiltration	After GAC/Feed to RO	Brine	Permeate
Turbidity (NTU):	31.7	0.15	0.15	9.2	<1
pH:	8.75	8.32	7.28	6.79	8.38
Conductivity (mS/cm):	8.74	8.52	8.04	13.25	0.23
TOC (mg/L):	93.58	86.28	0	0	0
Bicarbonate as CaCO <sub>3</sub> (mg/L)	150	N/A	170	300	11
Carbonate as CaCO <sub>3</sub> (mg/L)	54	N/A	26	54	ND
Total Alkalinity as CaCO <sub>3</sub> (mg/L)	200	N/A	200	360	11
Chloride (mg/L)	310	N/A	250	460	21
Sulfate (mg/L)	5100	N/A	4500	8900	54
Barium (mg/L)	ND	N/A	0.15	0.17	ND
Calcium (mg/L)	22	N/A	21	38	ND
Potassium (mg/L)	110	N/A	120	230	2.4
Magnesium (mg/L)	10	N/A	15	27	ND
Sodium (mg/L)	2200	N/A	2100	3700	44
Silicon as SiO <sub>2</sub> (mg/L)	ND	N/A	1.4	2.6	0.1
Silicon (mg/L)	ND	N/A	0.64	1.2	0.049
Strontium (mg/L)	0.25	N/A	0.58	1.1	ND

Raw water ion concentrations were tested by ALS Laboratory for Train 2 only to show how little they change in pretreatment steps before reverse osmosis. The same analysis was not conducted for Train 1 raw water, though similar results should be expected.

Overall, both Train 1 and Train 2 show very similar final water qualities. The average conductivities from both trains is are 0.32 and 0.23 mS/cm, both below the municipal drinking water conductivity of 0.346 mS/cm. Turbidity, pH, and TOC also compare favorably to Fairfield’s municipal drinking water quality.

## CHAPTER 5: PHASE III: COST ANALYSIS

### 5.1. Phase III Approach

From the initial project proposal, Colorado State identified that a cost analysis of some kind must occur. The initial objective states that CSU would “develop (a) cost model for Golden (Fairfield) plant to encompass alternatives for recycling including beneficial use and fraction of water recovered.” The scope for this phase of the research was intentionally specified to be vague until results from Phase II: Bench Scale Testing was completed. During bench scale testing and through communication with WaterTectonics, it was determined that a full cost analysis complete with a proposed return on investment (ROI) and estimated capital costs to implement the project was not feasible.

Instead, pilot scale treatment proposals were submitted by WaterTectonics. The pilot systems correspond to the two treatment trains described as the two alternatives from bench scale testing. Both pilots propose to treat 20 of the 80 GPM from the Fairfield plant for 60 or 90 day periods. Once the chosen pilot system has been fine-tuned and tested on site, WaterTectonics can contract with Ball Corporation directly to determine whether to build a full scale design treatment system. At this time, an ROI and estimated capital cost can more easily be provided and be more useful to all parties. The proposed pilot systems and their cost breakdowns are shown on the following pages. The first pilot corresponds to Train 1 (with electrocoagulation), while the second corresponds to Train 2 (without electrocoagulation). Total costs for 60 and 90 day trials are highlighted at the bottom of each pilot proposal.

Table 5.1: Train 1 – WaterTectonics Cost Proposal (With EC)

INDUSTRIAL - 20GPM Process Verification Program								
Item	Qty	Unit	Unit \$	Day	60	90	Comments	
<b>Equipment Lease</b>								
1	Process Tanks/Poly Tanks	6	Ea	\$ 15.00	\$ 90.00	\$ 5,400.00	\$ 7,290.00	Includes (6) vertical poly tanks
2	Feed Pumps & Level Controls	1	Ea	\$ 23.00	\$ 23.00	\$ 1,380.00	\$ 1,870.00	Includes (1) feed pump with level controls for automated operations
3	Ultra Skid - EC	1	Ea	\$ 162.00	\$ 162.00	\$ 9,720.00	\$ 13,130.00	Skid mounted 20GPM electrocoagulation with pump and control automation
4	Ultra Skid - UF	1	Ea	\$ 127.00	\$ 127.00	\$ 7,620.00	\$ 10,290.00	Skid mounted 20GPM ultra-filtration with pump and control automation
5	Chemical Pump and Injection	1	Ea	\$ 65.00	\$ 65.00	\$ 3,900.00	\$ 5,270.00	Chemical pump and control automation
6	Dissolve Air Flotation (DAF)	1	Ea	\$ 150.00	\$ 150.00	\$ 9,000.00	\$ 12,150.00	Includes sludge pump and air compressor for induced air activity
7	Reverse Osmosis (RO)/Brackish	1	Ea	\$ 235.00	\$ 235.00	\$ 14,100.00	\$ 19,040.00	GE Pro20; Feed Flow 20GPM with 50%-60% recovery
8	GAC Feed Pumps & Level Controls	1	Ea	\$ 23.00	\$ 23.00	\$ 1,380.00	\$ 1,870.00	Includes (1) feed pump with level controls for automated operations
9	GAC Polish Vessels	1	Ea	\$ 48.00	\$ 48.00	\$ 2,880.00	\$ 3,890.00	Includes filter vessel
10	Ultraflow Backflush and CIP Tanks	1	Ea	\$ 15.00	\$ 15.00	\$ 900.00	\$ 1,220.00	Includes (2) Poly Tanks
11	Interconnecting Hose Package	1	Ea	\$ 24.00	\$ 24.00	\$ 1,440.00	\$ 1,950.00	Covers rental of all hose required to interconnect system
<b>Equipment Lease Sub Total</b>					\$ 57,720.00	\$ 77,970.00		
<b>Consumables</b>								
					60	90		
12	Waveionics EC Treatment Cells		Ea	\$700.00		\$6,100.00	\$9,100.00	Flow based on (12) hours per day (7) days a week.
13	UF Membrane - Usage Fee	2	Day	\$ 7.00		\$840.00	\$1,260.00	WT is supplying membranes. CLIENT pays a daily usage fee from the start of operations. Membranes damage beyond normal-wear-tear during the project are billed at full value minus any rental paid. Prior to shipment WT performs two tests to confirm membrane performance 1) An inspection and record of the DP on the membranes at the design flow rate 2) 3rd party PSD test to confirm removal efficiency. WT allows for a 10% change in membrane performance between pre-deployment and post-deployment PSD testing results. Membrane rental begins upon arrival to site. UF membrane replacement cost is \$1,800 each. RO membrane replacement cost is \$689 each. Client owns RO membranes by the end of the 6 month of usage.
14	RO Membrane - Usage Fee	8	Day	\$ 7.00		\$3,360.00	\$5,040.00	
15	Granulated Activated Carbon (GAC)	1,500	lb	\$1.90		\$2,850.00	\$2,850.00	Replace as needed.
16	CIP Chemicals		Ea	\$100.00		\$400.00	\$600.00	Citric Acid, Preservative,
<b>Consumable Sub Total</b>					\$13,550.00	\$18,850.00		
<b>Services</b>								
17	System Mob and Commissioning	1	LS	\$14,850.00			\$14,850.00	Includes mobilization and commissioning of the treatment equipment listed above. Start-up & operations - if Required, support for System Start-Up and Commissioning- (1) WT Operator for 10 hr. Shift. Daily cost includes living expenses. AIRFARE and CAR RENTAL billed at cost. Excludes any required training for site work.
18	System Demobilization	1	LS	\$5,300.00			\$5,300.00	Includes tear down and demobilization of equipment for return, excludes all tank and vessel cleanouts and disposal
19	Daily Operations/Training	1	Ea	\$875.00	10		\$8,750.00	Includes 8hr operations by (1) WT technicians, living expenses included.
20	Freight In/Out	2	Ea	\$5,450.00			\$10,900.00	Includes freight inbound and outbound of the project. Placement of equipment with a mobile crane.

**Total Cost:**

**60 days - \$111,070**

**90 days - \$136,620**



Table 5.2: Train 2 – WaterTectonics Cost Proposal (Without EC)

INDUSTRIAL – 20GPM Process Verification Program (UF/RO ONLY)								
Item	Qty	Unit	Unit \$	Day	60	90		Comments
<b>Equipment Lease</b>								
1	Process Tanks/Poly Tanks	3	Ea	\$ 15.00	\$ 45.00	\$ 2,700.00	\$ 3,650.00	Includes (3) vertical poly tanks
2	Feed Pumps & Level Controls	1	Ea	\$ 23.00	\$ 23.00	\$ 1,380.00	\$ 1,870.00	Includes (1) feed pump with level controls for automated operations
3	Ultra Skid - UF	1	Ea	\$ 127.00	\$ 127.00	\$ 7,620.00	\$ 10,290.00	Skid mounted 20GPM ultra-filtration with pump and control automation
4	Reverse Osmosis (RO)/Brackish	1	Ea	\$ 235.00	\$ 235.00	\$ 14,100.00	\$ 19,040.00	GE Pro20; Feed Flow 20GPM with 50%-60% recovery
5	GAC Feed Pumps & Level Controls	1	Ea	\$ 23.00	\$ 23.00	\$ 1,380.00	\$ 1,870.00	Includes (1) feed pump with level controls for automated operations
6	GAC Polish Vessels	1	Ea	\$ 48.00	\$ 48.00	\$ 2,880.00	\$ 3,890.00	Includes filter vessel
7	Ultraflow Backflush and CIP Tanks	1	Ea	\$ 15.00	\$ 15.00	\$ 900.00	\$ 1,220.00	Includes (2) Poly Tanks
8	Interconnecting Hose Package	1	Ea	\$ 24.00	\$ 24.00	\$ 1,440.00	\$ 1,950.00	Covers rental of all hose required to interconnect system
<b>Equipment Lease Sub Total</b>					<b>\$ 32,400.00</b>	<b>\$ 43,780.00</b>		
<b>Consumables</b>								
13	UF Membrane - Usage Fee	2	Day	\$ 7.00		\$840.00	\$1,260.00	WT is supplying membranes. CLIENT pays a daily usage fee from the start of operations. Membranes damage beyond normal-wear-tear during the project are billed at full value minus any rental paid. Prior to shipment WT performs two tests to confirm membrane performance 1) An inspection and record of the DP on the membranes at the design flow rate 2) 3rd party PSD test to confirm removal efficiency. WT allows for a 10% change in membrane performance between pre-deployment and post-deployment PSD testing results. Membrane rental begins upon arrival to site. UF membrane replacement cost is \$1,800 each. RO membrane replacement cost is \$689 each. Client owns RO membranes by the end of the 6 month of usage.
14	RO Membrane - Usage Fee	8	Day	\$ 7.00		\$3,360.00	\$5,040.00	
15	Granulated Activated Carbon (GAC)	1,500	lb	\$1.90		\$2,850.00	\$2,850.00	Replace as needed.
16	CIP Chemicals		Ea	\$100.00		\$400.00	\$600.00	Citric Acid, Preservative,
<b>Consumable Sub Total</b>					<b>\$7,450.00</b>	<b>\$9,750.00</b>		
<b>Services</b>								
17	System Mob and Commissioning	1	LS	\$14,850.00			\$14,850.00	Includes mobilization and commissioning of the treatment equipment listed above. Start-up & operations - if Required, support for System Start-Up and Commissioning- (1) WT Operator for 10 hr. Shift. Daily cost includes living expenses. AIRFARE and CAR RENTAL billed at cost. Excludes any required training for site work.
18	System Demobilization	1	LS	\$5,300.00			\$5,300.00	Includes tear down and demobilization of equipment for return, excludes all tank and vessel cleanouts and disposal
19	Daily Operations/Training	1	Ea	\$875.00	10		\$8,750.00	Includes 8hr operations by (1) WT technicians, living expenses included.
20	Freight In/Out	2	Ea	\$5,450.00			\$10,900.00	Includes freight inbound and outbound of the project. Placement of equipment with a mobile crane.

**Total Cost:**

**60 days - \$79,650**

**90 days - \$93,330**

## CHAPTER 6: CONCLUSION AND RECOMMENDATION TO BALL CORPORATION

### **6.1. Conclusion and Recommendation**

Based on the testing and results provided by CSU, pilot cost proposals from WaterTectonics, and conversations with Ball Corporation, the recommendation from this report is that Ball Corporation proceed with the current project by selecting either the 60 day Train 1 trial or the 90 day Train 2 trial. The bench scale processes tested by CSU show that the pilot studies proposed by WaterTectonics should bring effluent wastewater back to municipal water quality. Train 1 would allow for Ball to test the entire process without as much risk of fouling the ultrafiltration membrane. Success in this trial would allow Ball to develop a full scale system, which would have the redundancy and consistency of added pretreatment. This system could likely be used at multiple locations around the world. Choosing Train 2 for 90 days would also be a viable option. This option is less expensive, and by adding the extra 30 days a longer testing time is provided to analyze the possible fouling of the ultrafiltration membrane. If the membrane fouls from being the initial pretreatment mechanism and receiving a high turbidity load, then coagulation is clearly needed. If not, then Ball Corp. can save money and proceed without the coagulation process.

### **6.2. Opportunities for Future Work**

The work summarized in this thesis shows the effectiveness of the bench scale treatment processes tested by CSU on one type of Ball Corporation wastewater. Further work could be done at different Ball Corporation manufacturing facilities. Ball Corporation produces a larger amount of wastewater at their glass bottling facilities than at their aluminum can manufacturing

facilities. Future work could be done at one of these sites to discover how water may be used more efficiently.

In regards to additional bench scale tests, bench scale dissolved air flotation analysis is an area of possible future experimentation. A bench scale dissolved air flotation unit was briefly tested in this project, but results were inconclusive. The bench scale DAF unit was impossible to measure quantitatively and showed no improvement over settling processes. Because the Fairfield plant already has a DAF unit active, no further research was conducted on this treatment process. Still it remains an area where future research could be done.

## CHAPTER 7: REFERENCES

- About Ball*. Ball Corporation, 2016. Web. 9 Feb. 2016. <<http://www.ball.com/about-ball/>>.
- Ball Corporation Overview*. Rep. Ball Corporation, May 2013. Web. 9 Feb. 2016. <[www.ball.com](http://www.ball.com)>.
- Chew, Chun M., Mohamed K. Aroua, Mohd A. Hussain, and Wan Ismail. "Evaluation of Ultrafiltration and Conventional Water Treatment Systems for Sustainable Development: An Industrial Scale Case Study." *Journal of Cleaner Production* 112 (2015): 3152-163. *Elsevier*. Web. 23 Feb. 2016.
- Dahm, Katharine, and Katie Guerra. *Produced Water Reuse Case Studies*. Rep. N.p.: U.S. Department of the Interior, Bureau of Reclamation, 2013.
- "Desalination Worldwide." *Seawater Desalination: Huntington Beach Facility*. Poseidon Water, 2010. Web. 25 Feb. 2016.
- Eagle, Jenny. "Ball Wins Brazilian Approval of Its Proposed \$8.2bn Rexam Deal." *FoodProductionDaily.com*. N.p., 14 Dec. 2015. Web. 09 Feb. 2016.
- Exec. Order No. B-29-15, 3 C.F.R. 2 (2014). Print. State of California
- Faunt, Claudia C., Randall T. Hanson, Kenneth Belitz, and Laurel Rogers. "Fact Sheet 2009–3057." *California's Central Valley Groundwater Study*. USGS, 9 Jan. 2013. Web. 11 Feb. 2016.
- Gibert, Oriol, Benoît Lefèvre, Marc Fernández, Xavier Bernat, Miquel Paraira, and Marc Pons. "Fractionation and Removal of Dissolved Organic Carbon in a Full-scale Granular Activated Carbon Filter Used for Drinking Water Production." *Water Research* 47.8 (2013): 2821-829. *ScienceDirect*. Web. 24 Feb. 2016.
- Holt, Peter K., Barton, Geoffrey W., and Cynthia A. Mitchell. *Chemosphere* 59 (2004): 355-67. *Elsevier*. Web. 18 Feb. 2016.
- Lahnsteiner, Josef, and Ferdinand Klegraf. "Industrial Water Reuse Case Studies." IWA Newsletter (2005): n. pag. Wabag, Nov. 2005. Web. 15 Feb. 2016.
- Mantell, Matthew, P.E, Minnich, Keith, and Tom Hayes. "Theme 2: Flowback Recovery & Water Reuse." Proc. of Proceedings of the Technical Workshops for the Hydraulic Fracturing Study: Water Resources Management, Washington, DC: US Environmental Protection Agency, 2011. 49-80. Print.
- Miller, G. Wade. "Integrated Concepts in Water Reuse: Managing Global Water Needs." *Desalination* 187.1-3 (2006): 65-75. *Research Gate*. Web. 11 Feb. 2016.
- National Research Council, and Water Sciences and Technology Board. *Water Reuse: Potential for Expanding the Nation's Water Supply through Reuse of Municipal Wastewater*. Washington,

- D.C.: National Academies, 2012. *California Government*. Committee on the Assessment of Water Reuse as an Approach to Meeting Future Water Supply Needs, 2012. Web. 27 Apr. 2016.
- Petersen, Robert J. "Composite Reverse Osmosis and Nanofiltration Membranes." *Journal of Membrane Science* 83.1 (1993): 81-150. *Elsevier*. Web. 25 Feb. 2016.
- Petricin, Irena, Jasmina Korenak, Damijan Povodnik, and Claus Helix-Nielsen. "A Feasibility Study of Ultrafiltration/reverse Osmosis (UF/RO)." *Journal of Cleaner Production* 101 (2015): 292-300. *Elsevier*. Web. 25 Feb. 2016.
- Prindle, William, and Andre De Fontaine. "A Survey of Corporate Energy Efficiency Strategies." *Water & Wastewater Infrastructure Energy Efficiency and Sustainability* (2013): 73-102. *Center for Climate and Energy Solutions*. Center for Climate and Energy Solutions, Nov. 2009. Web. 27 Apr. 2016.
- Rodrigues, Rafael T., and Jorge Rubio. "DAF—dissolved Air Flotation: Potential Applications in the Mining and Mineral Processing Industry." *International Journal of Mineral Processing* 82 (2006): 1-13. *Elsevier*. Web. 23 Feb. 2016.
- Ross, Charles C., P.E., and Brandon M. Smith, E.I.T. "Rethinking Dissolved Air Flotation (DAF) Design for Industrial Pretreatment." *Water Environment Federation* (2000): n. pag. *Purdue University Industrial Wastes Technical Conference*. Web. 23 Feb. 2016.
- Schoeberl, P., M. Brik, R. Braun, and W. Fuch. "Treatment and Recycling of Textile Wastewater - Case Study and Development of a Recycling Concept." *Desalination* 171 (2004): 173-83. *Elsevier*. Web. 16 Feb. 2016.
- Shaikih, Muhammad Ayaz. "Energy Conservation in Textile Industry." *Pakistan Textile Journal* (2009): n. pag. College of Textile Engineering, SFDAC, Nov. 2009. Web. 16 Feb. 2016.
- Stenzel, Mark H., and William J. Merz. "Use of Carbon Adsorption Processes in Groundwater Treatment." *Environ. Prog. Environmental Progress* 8.4 (1989): 257-64. Web. 24 Feb. 2016.
- Tang, Fang, Hong-Ying Hu, Li-Juan Sun, Ying-Xue Sun, Na Shi, and John C. Crittenden. "Fouling Characteristics of Reverse Osmosis Membranes at Different Positions of a Full-scale Plant for Municipal Wastewater Reclamation." *Water Research* 90 (2016): 329-36. *Science Direct*. Web. 25 Feb. 2016.
- The United Nations World Water Development Report 2015*. Paris: United Nations Educational, Scientific and Cultural Organization, 2015. *UNESCO*. Web. 10 Feb. 2016.
- Vik, Eilen A., Dale A. Carlson, Arlid S. Eikum, and Egil T. Gjessing. "Electrocoagulation of Potable Water." *Water Resources* 18.11 (1984): 1355-360. Web. 21 Feb. 2016.
- Walker, Steven, and Roberto M. Narbaitz. "Hollow Fiber Ultrafiltration of Ottawa River Water: Flootation versus Sedimentation Pre-treatment." *Chemical Engineering Journal* 288 (2015): 228-37. *Elsevier*. Web. 23 Feb. 2016.
- Wastewater Treatment for Refineries (n.d.): Waterleau. Web. 15 Feb. 2016.
- "What Is Electrocoagulation EC?" *WaterTectonics*. WaterTectonics, 2016. Web. 23 Feb. 2016.

## APPENDIX A: COAGULATION

Appendix A contains data and tables from the early water testing and coagulation trials. The initial test results from the ten raw water samples received by CSU over the testing period are shown in Table A.1. Sample #1 was first received in June 2015 and samples continued to be shipped until the Sample #10 was received in March 2016. Following this table, are coagulation results from iron, alum, and electrocoagulation testing. Alum and iron results (Tables A.2 and A.3) are single tests from Sample #2, while electrocoagulation testing and some filtration was conducted at the WaterTectonics lab in Everett, WA, with Sample #4 (Tables A.4 and A.5). Finally, Figure A.1 shows the calculator for electrocoagulation dosing used by WaterTectonics. Calculating the dose could be completed for flow through and batch treatment operations.

*Table A.1: Raw Water Samples*

	Sample #1	Sample #2	Sample #3	Sample #4	Sample #5
Turbidity (NTU)	18.80	24.70	4.10	39.40	20.20
Conductivity (mS/μm)	5.85	6.23	6.97	6.17	5.81
pH	9.26	9.59	9.93	10.43	10.05
TOC (mg/L)	128.00	121.00	104.00	104.00	107.00
	Sample #6	Sample #7	Sample #8	Sample #9	Sample #10
Turbidity (NTU)	37.20	17.50	22.00	18.10	31.70
Conductivity (mS/μm)	5.75	6.42	6.28	6.33	8.74
pH	10.11	9.45	9.65	9.65	8.75
TOC (mg/L)	108.00	92.35	99.48	96.23	93.58

Table A.2: Alum Coagulation Results, Single Tests from WS #2

Parameter	Jar 1	Jar 2	Jar 3	Jar 4	Jar 5	Jar 6
Coagulant Dose (mg/L)	25	50	100	150	200	250
Turbidity (NTU)	0.76	0.90	1.03	2.17	2.88	4.16
Conductivity (mS/ $\mu$ m)	5.85	6.10	6.17	6.15	5.98	6.19
pH	8.66	7.79	6.45	5.40	4.80	4.67
TOC (mg/L)	118	118	118	116	117	118

Table A.3: Iron Coagulation Results, Single Tests from WS #2

Parameter	Jar 1	Jar 2	Jar 3	Jar 4	Jar 5	Jar 6
Coagulant Dose (mg/L)	25	50	100	150	200	250
Turbidity (NTU)	1.72	2.18	7.35	99.90	203.00	322
Conductivity (mS/ $\mu$ m)	5.70	5.77	6.06	6.13	6.47	6.68
pH	7.98	7.37	4.28	3.18	2.90	2.76
TOC (mg/L)	116	116	118	118	119	115

Table A.4: After EC and 8 $\mu$ m Filtration Results, Single Tests from WS #4

Sample	1x Fe	1x Al	1x Mix	0.5x Fe	0.5x Al	0.5x Mix	2x Mix	Raw
Turbidity (NTU)	1.62	1.47	1.64	1.28	1.17	1.54	1.42	39.40
Conductivity (mS/ $\mu$ m)	6.26	6.18	6.18	6.18	6.11	6.17	6.18	6.12

Table A.5: After EC, 8 $\mu$ m, and 0.22 $\mu$ m Filtration Results, Single Tests from WS #4

Sample	1x Fe	1x Al	1x Mix	0.5x Fe	0.5x Al	0.5x Mix	2x Mix	Raw
Turbidity (NTU)	2.01	~0	~0	0.82	~0	~0	~0	~0
Conductivity (mS/ $\mu$ m)	6.19	6.09	6.09	6.04	6.05	5.98	6.05	6.15
pH	10.26	10.03	10.02	10.1	10.19	10.07	10.12	10.49

Flow Through EC dosing Calculator		Batch Treatment EC dosing Calculator	
Operating Amps	170	Operating Amps	1
Operating Time (seconds)	60	Operating Time (seconds)	23
Flow per cell (gpm)	85	Sample Volume (mL)	500
# of iron electrodes	4	# of iron electrodes	1
# of aluminum electrodes	4	# of aluminum electrodes	0
% Fe	50%	% Fe	100%
% Al	50%	% Al	0%
Coulombs	10200	Coulombs	23
Faradays	0.106	Faradays	0.000
moles e <sup>-</sup>	0.106	moles e <sup>-</sup>	0.000
moles Fe	0.026	moles Fe	0.000
moles Al	0.018	moles Al	0.000
grams Fe released	1.476	grams Fe released	0.007
grams Al released	0.475	grams Al released	0.000
mg Fe/L	4.5870	Fe Dose (mg/L)	13.3123
mg Al/L	1.48	Al Dose (mg/L)	0.00
Charge Loading (F/m <sup>3</sup> /min)	0.329	Charge Loading (F/m <sup>3</sup> )	0.477
Charge Rate (Coulombs/gpm)	120.00	Dosing Factor (x)	1.45
Dosing Factor (x)	1		

Figure A.1: WaterTectonics Electrocoagulation Calculator Spreadsheet



## APPENDIX B: ULTRAFILTRATION

Appendix B contains background tables and data for the ultrafiltration processes and trials conducted. Tables B.1-B.6 show the progression of filtration from 6 $\mu$ m to 0.2 $\mu$ m filtration for both chemical coagulants. All results are single tests from Sample #1. Table B.7 shows the complete list of dissolved substances tested by ALS Laboratory after ultrafiltration was conducted.

*Table B.1: Iron Coagulation after 6 $\mu$ m Filtration, Single Tests from WS #1*

Parameter	Jar 1	Jar 2	Jar 3	Jar 4	Jar 5	Jar 6
Coagulant Dose (mg/L)	25	50	100	150	200	250
Turbidity (NTU)	1.20	2.26	6.12	78.30	134.00	159.00
Conductivity (mS/ $\mu$ m)	5.67	5.57	5.81	6.11	6.50	6.59
pH	7.45	7.29	4.48	3.20	2.90	2.74
TOC (mg/L)	115	113	115	114	116	115

*Table B.2: Iron Coagulation after 1.5 $\mu$ m Filtration, Single Tests from WS #1*

Parameter	Jar 1	Jar 2	Jar 3	Jar 4	Jar 5	Jar 6
Coagulant Dose (mg/L)	25	50	100	150	200	250
Turbidity (NTU)	2.00	1.56	3.80	6.28	5.17	5.04
Conductivity (mS/ $\mu$ m)	5.12	5.47	5.93	6.29	6.24	6.71
pH	7.74	7.55	4.50	3.33	2.97	2.79
TOC (mg/L)	117	115	108	109	106	109

*Table B.3: Iron Coagulation after 0.2 $\mu$ m Filtration, Single Tests from WS #1*

Parameter	Jar 1	Jar 2	Jar 3	Jar 4	Jar 5	Jar 6
Coagulant Dose (mg/L)	25	50	100	150	200	250
Turbidity (NTU)	0.16	0.11	0.18	0.10	0.06	0.11
Conductivity (mS/ $\mu$ m)	5.13	5.50	6.19	6.33	6.31	6.45
pH	8.09	7.82	4.52	3.32	2.99	2.82
TOC (mg/L)	92	98	110	109	106	110

Table B.4: Alum Coagulation after 6 $\mu$ m Filtration, Single Tests from WS #1

Parameter	Jar 1	Jar 2	Jar 3	Jar 4	Jar 5	Jar 6
Coagulant Dose (mg/L)	25	50	100	150	200	250
Turbidity (NTU)	1.03	0.57	0.90	2.61	2.16	3.05
Conductivity (mS/ $\mu$ m)	6.30	6.03	5.69	6.04	5.96	5.74
pH	8.64	7.86	7.33	6.05	4.86	4.70
TOC (mg/L)	115	116	113	114	114	115

Table B.5: Alum Coagulation after 1.5 $\mu$ m Filtration, Single Tests from WS #1

Parameter	Jar 1	Jar 2	Jar 3	Jar 4	Jar 5	Jar 6
Coagulant Dose (mg/L)	25	50	100	150	200	250
Turbidity (NTU)	1.14	0.61	0.70	1.00	0.74	0.63
Conductivity (mS/ $\mu$ m)	6.06	5.93	5.67	5.94	5.81	5.89
pH	8.50	7.98	7.63	6.56	4.95	4.75
TOC (mg/L)	119	118	115	115	114	114

Table B.6: Alum Coagulation after 0.2 $\mu$ m Filtration, Single Tests from WS #1

Parameter	Jar 1	Jar 2	Jar 3	Jar 4	Jar 5	Jar 6
Coagulant Dose (mg/L)	25	50	100	150	200	250
Turbidity (NTU)	0.10	0.09	0.11	0.07	0.22	0.09
Conductivity (mS/ $\mu$ m)	6.32	6.01	5.78	6.07	5.79	6.08
pH	8.31	7.90	7.60	6.51	4.98	4.74
TOC (mg/L)	118	116	113	114	113	113

Table B.7: List of Dissolved Substances Tested by ALS Laboratories

ALS Tested Substances
Bicarbonate as CaCO <sub>3</sub> (mg/L)
Carbonate as CaCO <sub>3</sub> (mg/L)
Total Alkalinity as CaCO <sub>3</sub> (mg/L)
Ammonia as N (mg/L)
Bromide (mg/L)
Chloride (mg/L)
Fluoride (mg/L)
Nitrate as N (mg/L)
Orthophosphate as P (mg/L)
Sulfate (mg/L)
Boron (mg/L)
Barium (mg/L)
Calcium (mg/L)
Iron (mg/L)
Potassium (mg/L)
Magnesium (mg/L)
Manganese (mg/L)
Sodium (mg/L)
Silicon as SiO <sub>2</sub> (mg/L)
Silicon (mg/L)
Strontium (mg/L)
Sulfide (mg/L)

## APPENDIX C: GRANULAR ACTIVATED CARBON

Appendix C contains background tables and data for the granular activated carbon processes and trials conducted. Table C.1 shows the reduction in TOC within the contact test experiment for GAC. Table C.2 shows the exhaustion of GAC within the small scale GAC column. Finally, Tables C.3 – C.5 show the isotherm data for the optimal dose GAC trials. All trials are single tests which use water from Samples #5, 6.

*Table C.1: Contact Test Results in mg/L of TOC, Single Test from WS #5*

Coagulant and Dose	Contact Time (min)						
	0	10	20	30	60	90	120
Iron - 20 mg/L (TOC remaining in mg/L)	111	96	98	91	81	80	70
Alum - 30 mg/L (TOC remaining in mg/L)	111	97	93	91	81	78	71

Table C.2: GAC Exhaustion Curve Results, Single Test from WS #5 and 6

TOC Vial:	Volume Collected (mL)	TOC (mg/L)
1	25	4.80
2	50	8.36
3	75	11.39
4	100	14.53
5	125	16.62
6	150	19.06
7	175	20.62
8	200	22.51
9	225	24.61
10	250	24.57
11	275	25.75
12	300	27.25
13	325	27.42
14	350	28.83
15	375	30.07
16	400	30.22
17	425	31.54
18	450	32.10
19	475	32.09
20	500	32.22

Table C.3: GAC Isotherm Data – Electrocoagulation, Single Test from WS #5 and 6

Carbon Dosage (g/100mL)	Carbon Dosage (g/L) (M)	Concentration of Impurity Remaining (mg/L) ©	TOC Removed (X)	TOC Removed/ Unit Weight of Carbon (mg/g) (X/M)
0.00	0.00	85.00	0.00	0.00
0.4	4	70.64	14.36	3.59
1	10	49.23	35.77	3.58
2	20	34.60	50.40	2.52
3	30	21.06	63.94	2.13
5	50	10.77	74.23	1.48
8	80	5.06	79.94	1.00
10	100	1.40	83.60	0.84

Table C.4: GAC Isotherm Data – Iron Coagulation (20 mg/L), Single Test from WS #5 and 6

Carbon Dosage (g/100mL)	Carbon Dosage (g/L) (M)	Concentration of Impurity Remaining (mg/L) (C)	TOC Removed (X)	TOC Removed/ Unit Weight of Carbon (mg/g) (X/M)
0.00	0.00	102.00	0.00	0.00
0.4	4	87.71	14.29	3.57
1	10	64.77	37.23	3.72
2	20	41.56	60.44	3.02
3	30	30.14	71.86	2.40
5	50	20.21	81.79	1.64
8	80	15.04	86.96	1.09
10	100	12.77	89.23	0.89

Table C.5: GAC Isotherm Data – Alum Coagulation (30 mg/L), Single Test from WS #5 and 6

Carbon Dosage (g/100mL)	Carbon Dosage (g/L) (M)	Concentration of Impurity Remaining (mg/L) (C)	TOC Removed (X)	TOC Removed/ Unit Weight of Carbon (mg/g) (X/M)
0.00	0.00	105.00	0.00	0.00
0.4	4	84.71	20.29	5.07
1	10	59.94	45.06	4.51
2	20	39.32	65.68	3.28
3	30	27.86	77.14	2.57
5	50	19.72	85.28	1.71
8	80	14.44	90.56	1.13
10	100	13.70	91.30	0.91

## APPENDIX D: REVERSE OSMOSIS

Appendix D contains background tables and data for the reverse osmosis processes and trials conducted. Table D.1 shows the input data for the WinFlows models. This input data was based off of a single test and from the mixing of raw water Samples #3 and 4. Following this table are three figures (Fig. D.1 – D.3) which show the WinFlows input data interface and the results from the GE-AK and GE-CE membranes. The tables in Excel of the small scale reverse osmosis testing are shown in Tables D.2 and D.3. These tables are single results from Samples #2 and 6. Finally, a figure and table combination (Fig. D.4, Table D.4) show the difference in pH from iron coagulation to electrocoagulation. This table and figure are from the raw data in Tables D.2 and D.3.

Table D.1: WinFlows Input Data for TDS Concentrations, Single Test from WS #3+4

Dissolved Substance	Concentration	Measurement
Bicarbonate	140	mg/L as CaCO <sub>3</sub>
Carbonate	ND	mg/L as CaCO <sub>3</sub>
Total Alkalinity	140	mg/L as CaCO <sub>3</sub>
Ammonia as N	0.48	mg/L
Bromide	ND	mg/L
Chloride	47	mg/L
Flouride	ND	mg/L
Nitrate as N	ND	mg/L
Orthophosphate as P	ND	mg/L
Sulfate	3000	mg/L
Boron	1.5	mg/L
Barium	ND	mg/L
Calcium	9	mg/L
Iron	0.33	mg/L
Potassium	120	mg/L
Magnesium	2.8	mg/L
Manganese	0.013	mg/L
Sodium	1400	mg/L
Silicon as SiO <sub>2</sub>	0.25	mg/L
Silicon	0.12	mg/L
Strontium	0.15	mg/L
Sulfide	ND	mg/L



File Reports Options Help Language 语言

Water Type

**Feed Water Analysis**  
 Select Water Source: Brackish Surfacewater (Conventional) ▾  
 Select Water Type: User Defined ▾

Ion	mg/l	meq/l	ppm as CaCO3
Calcium (Ca)	9.22	0.4600	23.02
Magnesium (Mg)	2.87	0.2360	11.81
Sodium (Na)	1478.46	64.3087	3218.23
Potassium (K)	122.90	3.1434	157.31
Ammonia - N (NH4)	0.49	0.0239	1.19
Barium (Ba)	0.00	0.0000	0.00
Strontium (Sr)	0.15	0.0035	0.18
Iron (Fe)	0.34	0.0121	0.61
Manganese (Mn)	0.01	0.0005	0.02
<b>Total Cations</b>	<b>1614.44</b>	<b>68.1881</b>	<b>3412.37</b>
Sulfate (SO4)	3000.00	62.4584	3125.64
Chloride (Cl)	104.07	2.9355	146.90
Fluoride (F)	0.00	0.0000	0.00
Nitrate (NO3)	0.00	0.0000	0.00
Bromide (Br)	0.00	0.0000	0.00
Phosphate (PO4)	0.00	0.0000	0.00
Boron (B)	1.54	0.0436	2.18
Silica (SiO2)	0.26	0.0003	0.01
Hydrogen Sulfide (H2S)	0.00	0.0000	0.00
Bicarbonate (HCO3)	151.29	2.4794	124.08
Carbon Dioxide (CO2)	0.29	0.0000	0.00
Carbonate (CO3)	8.01	0.2670	13.36
<b>Total Anions</b>	<b>3265.16</b>	<b>68.1881</b>	<b>3412.37</b>

Multiple Feed  
 Design Guidelines  
 Add Sodium  
 Add Chloride  
 Clear Values  
 Balance

**Parameters**

Total Alkalinity (ppm CaCO3): 140.00  
 TDS (mg/l): 4879.60  
 pH: 8.84  
 Temperature (C): 15.00  
 SDI: 4.00  
 Recovery (%): 50

**Saturation Data (Feed Water)**

BaSO4: 0.00 %  
 CaF2: 0.00 %  
 CaSO4: 2.43 %  
 SiO2: 0.19 %  
 SrSO4: 2.11 %  
 Struvite: 0.000 %  
 LSI: 0.05  
 Stiff-Davis Index: -0.16  
 Osmotic Pressure: 30.89 psi  
 Conductivity at 25C: 6480 μS/cm  
 Density: 1002.6 kg/m3

Figure D.1: WinFlows Model Screen Shot – Influent Water Data Interface

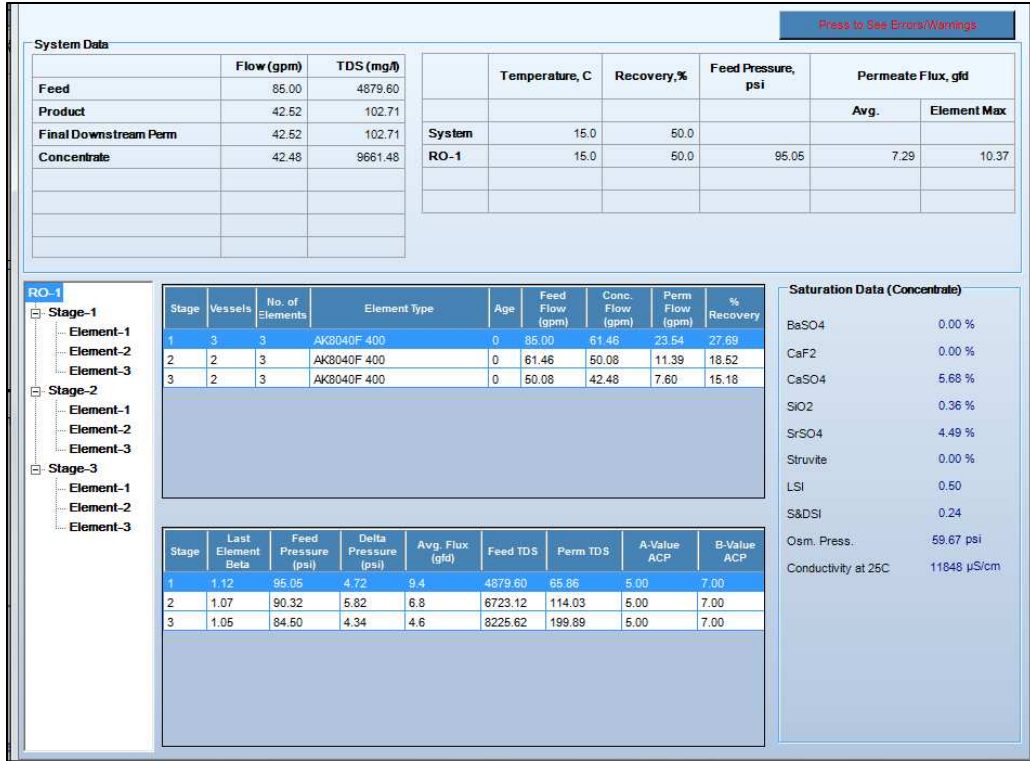


Figure D.2: WinFlows Model Screen Shot – Membrane GE-AK Results

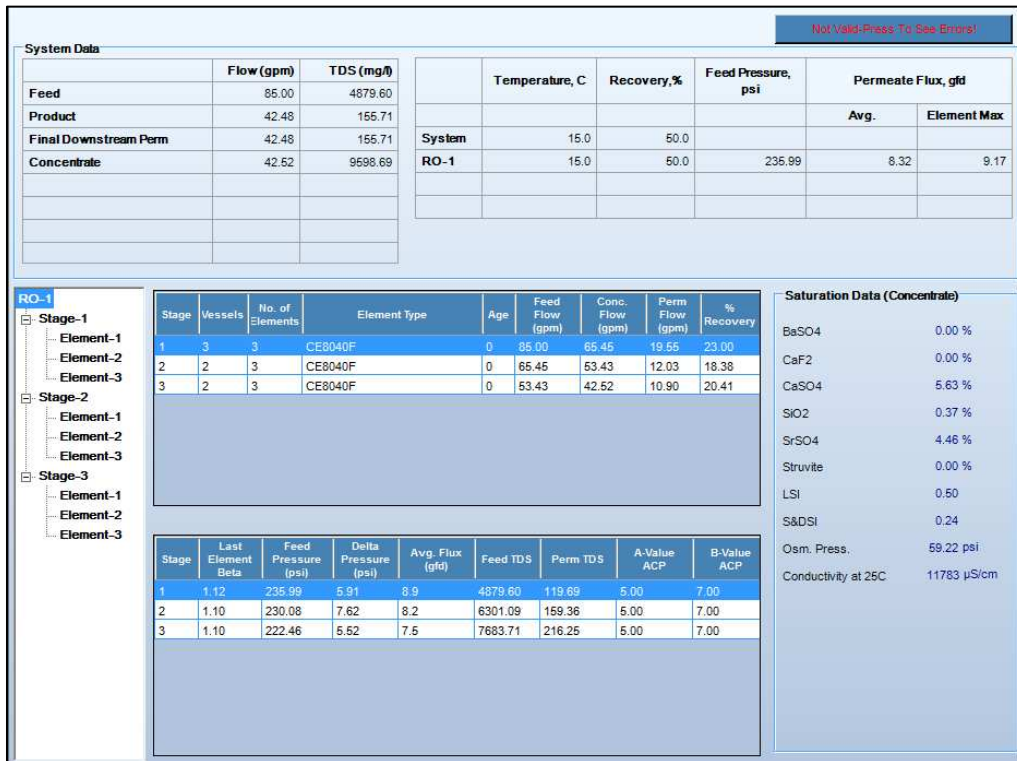


Figure D.3: WinFlows Model Screen Shot – Membrane GE-CE Results

Table D.2: Small Scale Reverse Osmosis Trials – Electrocoagulation, Single Tests from WS #2 and 6

EC:														
		Permeate: 25 mL				Brine: 25 mL								
		TOC (mg/L)	Cond. (mS/cm)	TDS (mg/L)	pH			TOC (mg/L)	Cond. (mS/cm)	TDS (mg/L)	pH	Membrane SA:	1734.945 mm <sup>2</sup>	
GE AG	No GAC:	7.65	0.51	640	7.87	No GAC:	169.90	10.75	9480	8.05	Membrane time:	110 min	Flux:	4.629538 GFD
Membrane	GAC Treated:	2.18	0.74	780	9.77	GAC Treated:	9.01	10.26	9280	9.41	Membrane time:	70 min	Flux:	7.274988 GFD
		TOC (mg/L)	Cond. (mS/cm)	TDS (mg/L)	pH			TOC (mg/L)	Cond. (mS/cm)	TDS (mg/L)	pH	Membrane SA:	1734.945 mm <sup>2</sup>	
GE AK	No GAC:	4.48	0.50	480	7.27	No GAC:	161.80	10.51	9140	8.23	Membrane time:	127 min	Flux:	4.009836 GFD
Membrane	GAC Treated:	0.60	0.32	520	9.89	GAC Treated:	5.16	11.20	9960	9.54	Membrane time:	70 min	Flux:	7.274988 GFD
		TOC (mg/L)	Cond. (mS/cm)	TDS (mg/L)	pH			TOC (mg/L)	Cond. (mS/cm)	TDS (mg/L)	pH	Membrane SA:	1734.945 mm <sup>2</sup>	
GE CE	No GAC:	7.30	0.18	440	7.82	No GAC:	141.3	10.23	9200	8.19	Membrane time:	63 min	Flux:	8.08332 GFD
Membrane	GAC Treated:	1.53	0.27	420	9.23	GAC Treated:	9.07	10.56	9600	9.48	Membrane Time:	60 min	Flux:	8.487486 GFD
		TOC (mg/L)	Cond. (mS/cm)	TDS (mg/L)	pH			TOC (mg/L)	Cond. (mS/cm)	TDS (mg/L)	pH	Membrane SA:	1734.945 mm <sup>2</sup>	
Toray	No GAC:	4.65	0.66	560	8.01	No GAC:	152.5	10.52	8880	8.38	Membrane time:	120 min	Flux:	4.243743 GFD
Membrane	GAC Treated:	-0.48	0.13	360	9.79	GAC Treated:	-4.902	9.61	8340	9.61	Membrane time:	70 min	Flux:	7.274988 GFD
		TOC (mg/L)	Cond. (mS/cm)	TDS (mg/L)	pH			TOC (mg/L)	Cond. (mS/cm)	TDS (mg/L)	pH	Membrane SA:	1734.945 mm <sup>2</sup>	
Triceps	No GAC:	2.354	0.32	440	8.1	No GAC:	143.8	10.65	9660	8.35	Membrane time:	90 min	Flux:	5.658324 GFD
Membrane	GAC Treated:	-0.51	0.18	320	10.18	GAC Treated:	-3.46	9.39	8340	9.58	Membrane time:	51 min	Flux:	9.985278 GFD

Table D.3: Small Scale Reverse Osmosis Trials –Iron Coagulation (20 mg/L), Single Tests from WS #2 and 6

Ferric Chloride:													
		Permeate: 25 mL				Brine: 25 mL							
		TOC (mg/L)	Cond. (mS/cm)	TDS (mg/L)	pH			TOC (mg/L)	Cond. (mS/cm)	TDS (mg/L)	pH		
GE AG	No GAC:	3.27	0.39	420	9.95	No GAC:	192.90	9.79	8700	9.43	Membrane SA:	1734.945	mm <sup>2</sup>
Membrane	GAC Treated:	1.56	0.22	460	10.25	GAC Treated:	27.05	10.02	8820	9.74	Membrane time:	121 min	Flux: 4.208671 GFD
											Membrane time:	60 min	Flux: 8.487486 GFD
GE AK	No GAC:	6.01	0.66	600	9.62	No GAC:	188.70	9.90	8540	9.24	Membrane SA:	1734.945	mm <sup>2</sup>
Membrane	GAC Treated:	3.39	1.75	1320	10.06	GAC Treated:	23.79	9.40	8280	9.75	Membrane time:	99 min	Flux: 5.143931 GFD
											Membrane time:	58 min	Flux: 8.780158 GFD
GE CE	No GAC:	9.67	0.11	280	9.29	No GAC:	183.90	9.81	8620	9.53	Membrane SA:	1734.945	mm <sup>2</sup>
Membrane	GAC Treated:	1.57	0.11	300	9.39	GAC Treated:	28.54	10.26	9000	9.90	Membrane time:	73 min	Flux: 6.976016 GFD
											Membrane time:	82 min	Flux: 6.210356 GFD
Toray	No GAC:	1.71	0.24	320	9.70	No GAC:	206.60	10.24	9260	9.58	Membrane SA:	1734.945	mm <sup>2</sup>
Membrane	GAC Treated:	0.10	0.44	460	10.00	GAC Treated:	23.57	9.76	9840	9.67	Membrane time:	144 min	Flux: 3.536453 GFD
											Membrane time:	88 min	Flux: 5.786922 GFD
Triceps	No GAC:	2.43	0.18	360	10.10	No GAC:	198.4	10.15	9020	9.23	Membrane SA:	1734.945	mm <sup>2</sup>
Membrane	GAC Treated:	-0.59	0.23	300	10.43	GAC Treated:	20.96	10.31	9280	9.71	Membrane time:	100 min	Flux: 5.092492 GFD
											Membrane time:	108 min	Flux: 4.71527 GFD

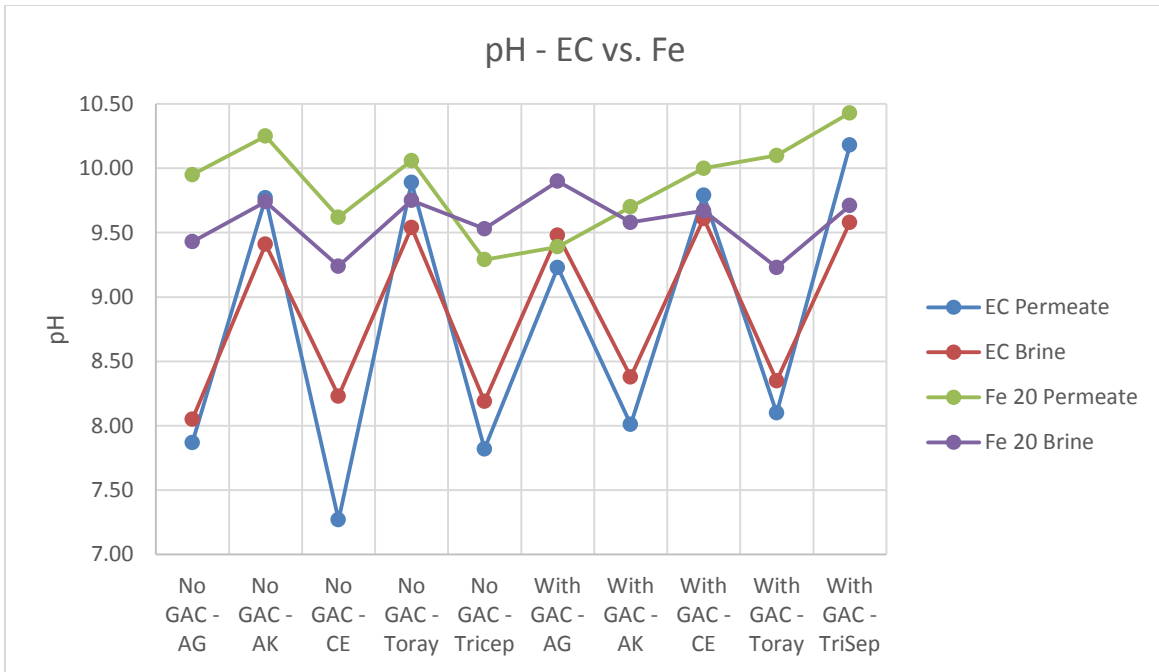


Figure D.4: Graph of pH Difference in Small Scale Reverse Osmosis Trials, Single Tests from WS #2 and 6

Table D.4: Table of pH Difference in Small Scale Reverse Osmosis Trials, Single Tests from WS #2 and 6

GAC - Membrane Type	pH Values for Each Trial			
	EC Permeate	EC Brine	Fe 20 Permeate	Fe 20 Brine
No GAC - AG	7.87	8.05	9.95	9.43
No GAC - AK	9.77	9.41	10.25	9.74
No GAC - CE	7.27	8.23	9.62	9.24
No GAC - Toray	9.89	9.54	10.06	9.75
No GAC - Tricep	7.82	8.19	9.29	9.53
With GAC - AG	9.23	9.48	9.39	9.90
With GAC - AK	8.01	8.38	9.70	9.58
With GAC - CE	9.79	9.61	10.00	9.67
With GAC - Toray	8.10	8.35	10.10	9.23
With GAC - TriSep	10.18	9.58	10.43	9.71