Sustainability in the Craft Brewing Industry: An Analysis of Tertiary Wastewater Treatments

A Senior Project
Presented to
The Faculty of the Liberal Arts and Engineering Studies Department
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Bachelor of Arts
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By Jessica Uibel
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Introduction

From boiling the hops, to bottling the beer, to washing and cleaning the brewing facilities, water is one of the top consumed resources in the brewing process. On average, it takes seven barrels of water to produce one barrel of beer ("Brewers Association Water"). Once used in the process, this water becomes wastewater that needs to be treated and recycled into potable water. There are two options for the treatment of this water: either send it to a treatment facility, or build an on site facility to filter and clean the water.

In the past, Firestone Walker's effluent was sent to the city of Paso Robles wastewater treatment plant. However, due to the company's growth, Firestone Walker's wastewater levels were exceeding the discharge limits set in the city of Paso Robles Municipal Code. Firestone Walker needed to lower these wastewater levels to comply with the city. To meet these requirements, the brewery began constructing an onsite wastewater treatment facility.

A wastewater treatment facility is made of three systems: primary, secondary, and tertiary. Primary treatment focuses on the separation of solids from the water, while secondary treatment is a biological process that focuses on reducing the biochemical oxygen demand (BOD). Both of these treatments are required to reduce the water levels to Paso Robles' acceptable standards. However, while ending after the secondary treatment and sending the water back to the city would meet the municipal code requirements, it would be unlikely to meet the Return on Investment (ROI) for building the treatment facility. To meet this ROI, the tertiary treatment is introduced into the system. This treatment focuses on removing any remaining solids and disinfecting the water so it can be reused by Firestone Walker. The brewery plans to reuse the water in three ways: steam generation, evaporative coolers, and wash-down.

Wastewater treatment and recovery is an important issue to study since, "despite significant improvement over the last 20 years, water consumption and wastewater disposal remain environmental and economic hurdles that directly affect breweries and the brewing process" ("Brewers Association Water"). For breweries, the difficulties lay in the high sugar content, the high alcohol content, and the wide range of pH found in the water. However, these issues are not limited to breweries, but are faced across all industries, with each segment having its own difficulties in treatment. Finding ways to improve the recovery of wastewater is a topic that will continue to be studied, as wastewater treatment is an ongoing challenge.

Research Question:

What is the optimal tertiary water treatment to maximize the amount of water reclaimed, and minimize the time to achieve the Return on Investment, for a wastewater treatment facility at a craft brewery?

Deliverables

Upon completion of Liberal Arts and Engineering Studies 462, this project will contain the following four deliverables:

1. *Senior Project Written Component*

   The Senior Project Written Component details factors of the project including literature review, technology overview, project design and implementation, analysis and verification of project success, societal impacts, future work, conclusion, and references.

2. *Recommended Tertiary System Report for Firestone Walker (Appendix D)*

   This report recommends which systems Firestone Walker should invest in for their wastewater treatment facility. The report includes a definition of the system requirements, a comparison between different filtration and disinfection systems, an analysis of the recommended system (for cost, performance, and design), an estimated ROI for the system, and a brief description of best practices for the three reuse purposes.

3. *Wastewater Treatment: Facilities and Pretreatment Certification (Appendix A)*

   This certification was awarded by Sacramento State University's Office of Water Programs and represents the completion of the Facilities and Pretreatment course for wastewater treatment operators. This course introduced the principles of operating and maintaining a wastewater treatment facility as well as in depth lessons on preliminary wastewater treatment. The course contained 18 hours of material, and completion of the course earned 1.8 Continuing Education Units.

4. *Wastewater Treatment: Disinfection Certification (Appendix B)*

   This certification was awarded by Sacramento State University's Office of Water Programs and represents the completion of the Disinfection course for wastewater treatment operators. This course introduced the three main types of disinfection (chlorination, ozone, and ultraviolet), with an emphasis on chlorination systems and dechlorination techniques. The course contained 18 hours of material, and completion of the course earned 1.8 Continuing Education Units.

Literature/Technology Review

Several literary sources helped complete this research project, including past Cal Poly Senior Projects and studies completed by other breweries. Each source helped in one or more factors of the project; however, due to the uniqueness of this project, several sources were combined to provide adequate background information on current wastewater treatment techniques.

One challenge this literature review uncovered was the trend of breweries to recover energy from their wastewater, rather than water. Only one craft brewery, Stone Brewing Company, was able to disclose that they recovered water. However, Stone Brewing Company had different reuse purposes and tertiary treatments than Firestone Walker Brewing Company.

Additionally, the performance of wastewater treatment facilities is highly plant-specific, as effluent levels are sensitive to the flow rate and water quality levels of the influent. Due to this variability, any numbers obtained for the Firestone Walker report could only serve as guidelines, since accurate estimations can only be found through experimentation at the plant. Below is a brief summary of the literature reviewed for this report.

1. *Cost-Benefit Analysis of Implementing Wastewater Treatment Facilities in Beer Breweries - A Senior Project Report conducted by Jeff Shah-Ganai*

   Shah-Ganai's report, found from the Cal Poly Digital Commons, determined that for medium to large scale breweries, it is recommended to invest in installing a wastewater treatment facility. Although the report did not have a defined client, and was conducted with several estimated figures, the conductor drew information from Sierra Nevada Brewery, Red Hook Brewery, and Central Coast Brewing to determine its recommendation. Shah-Ganai's findings aided this report by providing guidelines for performing a cost-benefit and net present value analysis on the facility.

2. *Optimization of an Industrial Wastewater Treatment Plant through Implementation of a Membrane Bioreactor and Reverse Osmosis System for Reuse by Naomi Jones*

   Stone Brewing Company faced a challenge similar to Firestone Walker, as the city of Escondido charged a higher water fee since the brewery's wastewater surpassed the city's discharge limits. To avoid this fee, the brewery implemented an onsite wastewater treatment system. The main difference in Stone Brewing Company's system was the decision to use a Membrane Bioreactor (MBR) – Reverse Osmosis (RO) combination, rather than Aerated Pond – RO combination. Beyond the system, differences also existed in the reuse purposes, as Stone Brew Co. did not need to disinfect their effluent. However, the study aided this report by providing estimates on RO effluent quality from brewery process wastewater – an estimate that is otherwise difficult to find. Although Firestone Walker was recommended to implement a Nanofiltration (NF) system rather than RO, the effluent estimations helped ensure that the recommended system would match the Title 22 requirements for tertiary treated water.

3. *Pilot Investigation of Slow Sand Filtration and Reverse Osmosis Treatment of Central Arizona Project Water by Charles Moody, Bruce Garrett, and Eric Holler*

   To verify that Slow Sand Filtration (SSF) was a feasible option for RO filtration, the study completed by the U.S. Department of the Interior Bureau of Reclamation served as a guideline for this project. The study found that using SSF systems met the requirements needed for pre-RO treatment, and that the capital costs for implementing an SSF-RO system was less than the conventional method of using Ultrafiltration (UF)-RO. Since RO has stricter filtration requirements than NF, it was assumed that SSF would also be a feasible option for NF systems.

4. *Slow sand/Nanofiltration of Surface Water by C. Brent Cluff from University of Arizona*

   This study verified that combining SSF and NF treatments is not only a feasible option, but also an economically justifiable option. According to this study, water from the Colorado River was recovered at a rate of 95% consistently over a two-year period. This finding shows that SSF-NF is a long term, viable option for groundwater treatment.

Beyond these four studies, several other pieces of literature were used to complete this research. A complete list can be found under the References heading. However, the main concepts learned through the literature review were that (1) SSF is a feasible option for RO/NF filtration, (2) SSF-RO systems cost less than UF-RO systems, and (3) SSF-NF systems are feasible for long-term water recovery.

Technology Overview

To fully understand the necessity of tertiary treatments, a brief introduction to wastewater treatment facilities is given below. Following this introduction is a discussion of the different tertiary system, with emphasis placed on the recommended systems.

Brief Introduction to Wastewater Treatment Facilities

There are typically three systems in a wastewater treatment facility. The first, primary, is defined as the “removal of a portion of the suspended solids and organic matter from the wastewater.” Following this step is secondary treatment, which is the “removal of biodegradable organic matter and suspended solids” from the water. The last step, tertiary, is defined as the “removal of residual suspended solids usually by granular medium filtration of micro screens” (Tchobanoglous, Burton, Stensel). At Firestone Walker, it was important to understand which techniques were used for primary and secondary treatments to project an accurate estimate of water influent levels into the tertiary system.

Before looking into Firestone Walker’s current facility, an explanation of the different properties of wastewater will be valuable to understand the treatment goals. First, there are three main issues that are addressed in wastewater treatment – pH, biochemical oxygen demand (BOD), and total suspended solids (TSS). BOD measures the nutrient value of the water, and TSS measures the suspended solids in the water (Mercer). According to the Brewer's Association, "Effluent from fermentation and filtering are high in BOD and low in volume, accounting for about 3% of total wastewater volume but 97% of BOD. The average pH of combined effluent is around 7. But this [value] can fluctuate from 3 to 12 depending on the use of acid and alkaline cleaning agents" ("Brewers Association Water").

At Firestone Walker, treatment starts with a rotary screening, which serves as a preliminary solids separation; objects larger than 0.25" are sent down a gravity line. A secondary screening then occurs, where a wedge wire screening filters out objects larger than .02". This filtered water then enters a pH adjustment vault. After this adjustment, the water enters the aerated lagoons for BOD treatment. The water can stay in these lagoons for several months to ensure maximum BOD removal. After leaving the lagoons, the water has completed its secondary treatment, and is ready to enter the tertiary treatment for removal of TSS and pathogens.

Typically, tertiary treatments use a membrane process, such as Nanofiltration or Reverse Osmosis, to treat the water. However, since the membranes within these systems can easily be damaged and are susceptible to fouling, a filtration system is necessary to maximize longevity of the membranes. Then, depending on the final use of the reclaimed water, a disinfection system may be necessary. Appendix C lists summary of disinfection requirements. Firestone Walker will require disinfection for their reuse purposes.

<u>Filtration Systems</u>: Three different filtration systems were evaluated for Firestone Walker – Ultrafiltration (UF), Rapid Sand Filtration (RSF), and Slow Sand Filtration (SSF). A decision matrix was created to compare the features of the systems and decide which system would be best for the brewery. The matrix is located in Appendix D under the heading, "*Decision Matrix for Considered Systems*."

The system with the lowest score, Slow Sand Filtration, was recommended as the brewery's filtration system. The benefits of a SSF system are the lower capital costs, relative ease of operation and maintenance, and avoidance of chemicals or energy for operation. The disadvantages of SSF systems are the large area required for operation and the strict influent requirements.

Slow Sand Filters are essentially comprised of a layer of sand, through which the water is gravity fed to a collection bin at the bottom of the basin. As the water begins filtering through the sand, a biological layer called the schmutzdecke forms above the sand. This layer helps to remove both sediments and pathogens by establishing a community of predatory bacteria that feed on the microbes passing through the filter. When water enters the supernatant water feed (the layer of water above the sand), it takes between 3-12 hours to filter through the system. Due to this slow filtration rate, multiple basins are necessary to maintain the flow rate through the tertiary system (Bruni).

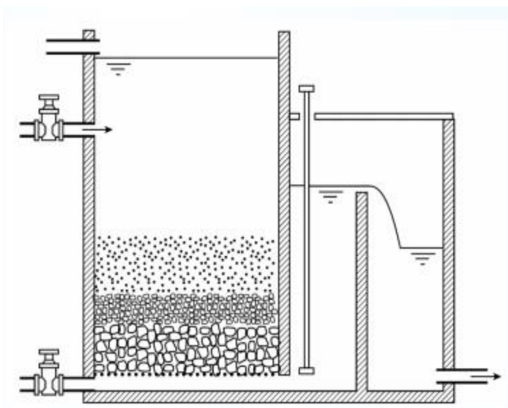

Figure 1. Slow Sand Filtration General Design

Membrane System: Although Firestone Walker originally planned on implementing a Reverse Osmosis system, the final recommendation was to instead use an NF system. Both RO and NF systems are membrane systems; however, Nanofiltration has a slightly larger pore size, allowing more particles into the permeate. Reverse Osmosis systems are primarily used for brackish water, or water with a high salt content. To avoid salts in the permeate, the pore sizes are smaller, and therefore the percentage of water recovered shrinks; typical water recovery (with two stages of RO) can be between 65%-75%. Nanofiltration is a feasible, less expensive option when the influent water is not expected to have a high salt content. NF systems have an average water recovery of 85%-95% and operate at a lower water pressure.

Figure 2. Example of a Nanofiltration System

Nanofiltration systems use hydraulic pressure to overcome the osmotic pressure from passing the feed solution through a semi-permeable membrane. This pressure pushes the water (and any particles smaller than the pores) through the membrane. All particles that cannot pass through the membrane become part of the system concentrate and are either recycled back through the system or discharged (Li, Ehund, and Wang).

Disinfection System: Three different disinfection systems were evaluated for Firestone Walker – Chlorination, Ultraviolet (UV), and Ozone. A decision matrix was created to compare the features of the systems and decide which system would be best for Firestone Walker. The matrix can be seen in Appendix D under the heading, "*Decision Matrix for Considered Systems*."

The system with the lowest score, UV, was recommended for Firestone Walker. The benefit of UV systems includes the quality of treatment without the use of chemicals or creation of dangerous by-products. However, the disadvantage of UV systems is the higher energy requirement to continuously power the UV lamps.

UV systems operate by exposing the DNA and RNA of microorganisms in the water to UV radiation, damaging this genetic material so that the cell can no longer grow or reproduce, effectively killing the cell and rendering it harmless ("WAT601E").

Figure 3. Example of Ultraviolet System

Design

The design of this project followed the DMAIC approach. DMAIC is a framework used in Lean/Six Sigma projects, and it stands for Define, Measure, Analyze, Improve, and Control. Each step of the project followed the framework, and details of each step, shown on the left axis of the timeline in Figure 4, are described in the following paragraphs.

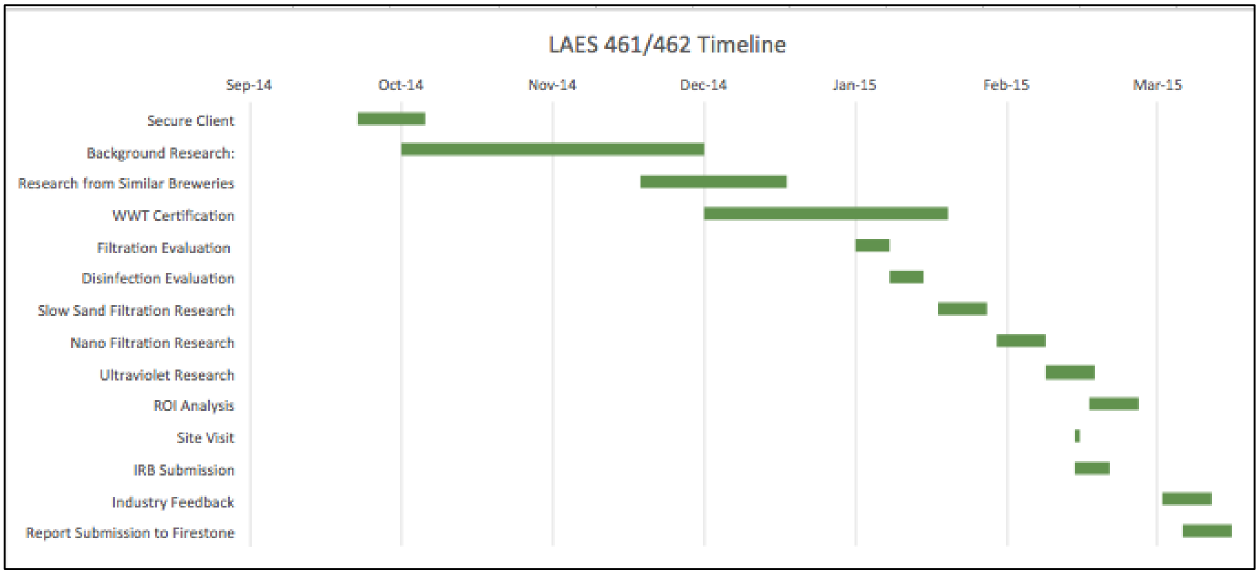

Figure 4. Project Timeline: An overview of the project timeline from September 2014 to March 2015

Define

Steps that took place in the Define portion of the project include (1) Securing a Client, (2) Background Research of Wastewater Treatments, (3) Research from Similar Breweries, and (4) Wastewater Treatment Certifications.

<u>Securing a Client</u>: While the original idea behind this study always focused on Sustainable Brewing, the topic required a narrowed scope. An email explaining the project was sent to nine breweries within the San Luis Obispo area. Responses were received from four of the nine breweries, with two of the four interested in learning more about the project (Firestone Walker Brewing Company and Dunbar Brewing). Of those two, Firestone Walker was chosen due to its ability to narrow the project scope to Wastewater Treatment.

<u>Background Research of Wastewater Treatment Plants</u>: Prior to this project, I had limited knowledge of wastewater treatment. Background research on different systems was essential to ensure all aspects of installing a system were considered. The online Sacramento State University courses, mentioned under the Deliverables heading, provided a strong understanding of pre-treatment and disinfection. Information on the remaining topics was found from various sources, including the Environmental Protection Agency and the World Health Organization.

<u>Research from Similar Breweries</u>: To determine which systems to research, the 16 breweries in Table 1 were contacted by email to obtain information regarding their wastewater treatment facilities. Each brewery ranked above Firestone Walker on the Brewers Association’s list of the Top 50 Breweries in 2013 (“Brewers Association Lists”).

Brewery Name	Wastewater Treatment Facilities
Alaskan Brewing Co.	No
Abita Brewing Co.	Yes: Anaerobic BERS System
Shipyard Brewing Co.	No
Dogfish Head Craft Brewery	No
Harpoon Brewery	Yes: Unknown System
Matt Brewing Co.	Yes: Unknown System
Stone Brewing Co.	Yes: MBR-RO
Brooklyn Brewing Co.	No
Duvel Moortgar USA	Yes: Aerobic Digestion
Bell's Brewing Co.	No
Deschutes Brewery	Yes: Unknown System
Lagunitas Brewing Co.	Yes: Unknown System
Gambrinas	No
New Belgium Brewing Co.	Yes: Aerobic and Anaerobic Digesters
Sierra Nevada Brewing Co.	Yes – Biothane Anaerobic Digesters
Boston Beer Co.	Yes – Unknown System

Table 1. Brewery Comparison: These sixteen breweries all ranked higher than Firestone Walker on sales volume for 2013 and were contacted for information regarding onsite wastewater treatment facilities.

Several breweries did not respond to the email. Of those that did, only one brewery, Stone Brewing Company, treated the wastewater with the goal of reclaiming water for reuse. Although the brewery's system differed from Firestone Walker's, the information helped provide estimates for Firestone Walker's recommendation. Details of the report from Stone Brewing Co. can be found under the Literature Review heading.

Wastewater Treatment Certification: As mentioned in the Deliverables heading, wastewater operator certifications were earned for two courses taken through the Sacramento State University: Facilities and Pretreatment, and Disinfection. More information about the certifications is discussed under the Deliverables heading.

Measure

The measure phase included two steps: (1) Filtration Evaluation and (2) Disinfection Evaluation. The goal of each evaluation was to measure the comparable systems based on several criteria to select the best tertiary treatment for Firestone Walker. An explanation of these evaluations can be found under the previous heading, Technology Overview.

Analyze

Based off the results of the measure phase, the analyze phase took a deeper look into the costs, performance, and designs of the recommended system: (1) Slow Sand Filtration, (2) Nanofiltration, and (3) Ultraviolet. An explanation of this systems can be found under the previous heading, Technology Overview.

Implement

Although usually called the Improve phase, this stage was adapted to become the implement phase and looked at the total costs associated with implementing the recommended system.

Return on Investment Analysis: As it was difficult to obtain an accurate cost (both capital and operations/maintenance), a return on investment matrix was created to account for the flexibility in capital spent and percentage of water reclaimed. The matrix (found in Appendix D), spans capital costs of $250,000 to $450,000 and water reclamation rates of 50% - 90%. It was created based off an annual growth rate of 25% from the 2014 water production values. Based off of the current cost estimation and water reclamation rates, Firestone Walker is expected to see a return on investment within 14-16 months.

Control

The last phase of the DMAIC cycle, the control phase, is meant to assess the success of work done in previous phases. For Firestone Walker, the system could not be assessed since it was not yet installed, so instead best practices were recommended to ensure minimal water usage with evaporative coolers and steam generation. For this report, work was assessed using the analysis and verification of project success, which can be found under the next heading.

Best Practices: The best practices for steam generation and evaporative cooling were adapted from the Brewers Association's report on wastewater treatment and reduction. The recommendations can be found in Appendix D under the heading, "*Best Practices*."

Analysis and Verification of Project Success

To determine the success of this project, three factors contributed to the verification of project success: (1) Satisfaction of Firestone Walker, (2) Increased Knowledge of Wastewater Treatments, and (3) Increased Marketability to Future Employers.

1. Satisfaction of Firestone Walker Brewing Company
   As Firestone Walker's tertiary Wastewater Treatment facility would have been implemented without the aid of this study, a critical factor in the success of this report was the level of satisfaction from Firestone Walker. To rank this level of satisfaction, Mark Fisher, Plant Engineer at Firestone Walker, was sent the Firestone Walker Tertiary Treatment Report. After reading the report, he evaluated the work and ranked it on accuracy, thoroughness, and helpfulness. To be considered successful, I needed a minimum evaluation of 4/5 for accuracy, 3/5 for thoroughness, and 3/5 for helpfulness.

   As seen below in Figure 5, the report received a score of 5 in all three categories, meeting each of the criteria for success. In addition to these ranking, Mark Fischer was asked two questions regarding the work. The questions and answers are stated below Figure 5.

	Accuracy	Thoroughness	Helpfulness
0	Report contains a lot of inaccurate information and none of the information is applicable	Report considers one feasible treatments systems and does not evaluate the ROI	Firestone Walker will not choose the recommended system, and the report contains no helpful information
1	Report contains some inaccurate information, and none of the information is applicable	Report considers few feasible treatment systems and evaluates the ROI with only one factor	Firestone Walker will not choose the recommended system, but report contains some helpful information
2	Report contains some inaccurate information, but the information is mostly applicable	Report considers few feasible treatment systems and evaluates the ROI with few associated costs	Firestone Walker will not choose the recommended system, but report contains a lot of helpful information
3	Report contains accurate information, and most of the information is not applicable	Report considers most of the feasible treatment systems and evaluates the ROI with most of the associated costs	Firestone Walker will choose one portion of the recommended system
4	Report contains accurate information and most of the information is applicable	Report considers all feasible treatment systems and evaluates the ROI with most of the associated costs	Firestone Walker will choose two portions of the recommended system
5	Report contains accurate information and all of the information is applicable	Report considers all feasible treatment systems and evaluates the ROI with all associated costs	Firestone Walker will completely choose in the recommended system

Accuracy Score: 5 Thoroughness Score: 5 Helpfulness Score: 5

Figure 5. Rubric for evaluating the success of the project, with the scores filled in by Firestone Walker Plant Engineer, Mark Fischer.

Q1: How did the work compare to the level that would be expected from a Firestone Walker Employee?
A: Outstanding. This report presents a very comprehensive understanding of filtration practices.

Q2: Are there any other comments you would like to make regarding the success of this project?
A: The findings outlined in the report will be extremely helpful by helping us [Firestone Walker] make the right decision with regards to tertiary treatment. Also, the ROI matrix will be greatly appreciated by Adam Firestone.

2. Increased Knowledge of Wastewater Treatment

To be successful in this study, I needed to prove that enough knowledge about treating wastewater had been gained to support the recommendations made. This knowledge was gained by completing two online wastewater treatment courses through Sacramento State University. I needed to pass both courses with a 70% or better.

The first course, Facilities and Pretreatments, was passed with a score of 94.42%. The second course, Disinfection, was passed with a score of 83.25%. Both of these scores surpassed the minimum requirement of 70%, resulting in certification. Images of the certification can be seen in Appendices A and B.

3. Increased Marketability to Future Employers

The topic of wastewater treatment was chosen to give me an opportunity to complete an independent project, one that required knowledge gained from outside of the LAES curriculum. To be successful, both the choice of topic, and the demonstrated skill of autonomous learning, must aid in my marketability to future employers.

To gauge this success, Industrial Engineers (all being Cal Poly Alumni) from fifteen potential employers were contacted among different industries of interest. Each professional was sent the following message on LinkedIn:

My name is Jessica Uibel, and I'm current a Senior at Cal Poly, majoring in Liberal Arts and Engineering Studies with a concentration in Industrial Engineering. I am writing to you in regards to my Senior Project in hopes that you can help evaluate one factor of success for my project: Marketability to Employers. If you wish to participate, it should only take a few moments of your time.

For my Senior Project, I am researching tertiary waste water treatment systems. Since this topic is not widely studied or applicable within the IE field, I am gathering data to see if this project is increasing my marketability to potential future employers. Along with the knowledge of waste water systems, the main skills I am gaining are autonomous learning, taking advantage of available resources, and project management.

My question to you is: Would my experience with Waste water Treatment Facilities influence my probability of obtaining an interview for an Industrial Engineering related job at your company? Please reply with a ranking from the criteria below:

0: No effect on applicant pool
1: Brings candidate to top 50%
2: Brings candidate to top 40%
3: Brings candidate to top 30%
4: Brings candidate to top 20%
5: Brings candidate to top 10%

Thank you very much for your time and feedback,

Jessica Uibel
Liberal Arts and Engineering Studies
Cal Poly San Luis Obispo

To be successful, an average minimum score of 3 needed to be earned, meaning the project would bring me to the top 20% of applicant pools. A summary of the scores can be found in Table 2.

Company	**Score**	**Meaning**
Raytheon	0	No effect on applicant pool
Lockheed Martin	4	Brings Candidate to top 20%
Genentech	2	Brings Candidate to top 40%
Apple	0	No effect on applicant pool
Disney	0	No effect on applicant pool
Average	1.25	Brings Candidate to top 47.5%

Table 2. Increased Marketability Scores

The average score of 1.25 did not meet the minimum score of 3/5. However, professionals from Apple and Disney responded by saying that the project would not help with obtaining an interview since the selection is largely online, but that the experience would be valuable to discuss during an actual interview. Although this criterion is ranked as not successful, it provided a valuable learning experience and insightful feedback about acquiring an interview at a large corporation.

In summary, five of the six factors surpassed the minimum requirement for success. A summary of the criteria for success can be found in Table 3.

Criteria	Minimum Ranking	Actual Ranking	Successful
1.1 Accuracy Score	4/5	5/5	Yes
1.2 Thoroughness Score	3/5	5/5	Yes
1.3 Helpfulness Score	3/5	5/5	Yes
2.1 Certification Exam #1 Results	70%	94.42%	Yes
2.2 Certification Exam #2 Results	70%	83.25%	Yes
3.1 Increased Marketability	3/5	1.25/5	No

Table 3. Summary of Criteria for Success

Societal Impacts

The wastewater treatment facility at Firestone Walker Brewing Company has three main impacts on society: (1) Impact on Paso Robles, (2) Impact on Future Firestone Walker locations, and (3) Impact on Future Wastewater Treatment Facilities.

Locally, the facility at Firestone Walker will have a mild impact on the city of Paso Robles. As the community continues to suffer through the current drought, recycling water onsite at Firestone Walker will reduce the daily load of water to the city's wastewater treatment plant. This reduction (and higher quality) of influent to the plant will allow it to focus its time and resources on recycling domestic wastewaters, rather than putting effort towards correcting the brewery's wastewater levels.

Within Firestone Walker Brewery Company, the techniques learned through implementing this wastewater treatment facility can be applied to their breweries in Buellton and Venice, should those cities enforce an onsite wastewater facility. Having the experience of building and operating the site in Paso Robles will set a guideline, and establish best practices, for constructing and operating future wastewater treatment facilities within the company.

Lastly, since the recommendation of using a SSF-NF-UV system goes against the traditional implementation of a UV-RO-UV system, other companies, including those outside of the brewing industry, can learn from the example set by Firestone Walker. Seeing this combination successfully treat wastewater may encourage other companies to install an onsite facility, since this combination has a lower capital cost and recovers a higher percentage of water than the traditional system combination.

Future Work

There are two opportunities for future work following the completion of this project. The first focuses on further water reclamation, while the second focuses on the feasibility of reclaiming energy from Firestone Walker's wastewater.

Currently, one pretreatment step in Firestone Walker's facility is solids separation. During this step, water is passed through a screen with a .02" opening. Anything in the water larger than this gap is sprayed into a collection bin. This step will use between 600-1000 gallons of water on a weekly basis. Although this is a small amount of water relative to the brewery's daily flow (approximately 90,000 gallons), over a year this step will use 31,200 – 52,000 gallons of water. Reclaiming this water, possibly through an activated carbon back-flush system, would help decrease the overall water usage of the brewery. But, the return on investment of this system would need to be analyzed to determine if it's a practical investment.

The second future project would be a feasibility study for reclaiming energy through an anaerobic digester. Many companies in the brewing industry choose to treat their wastewater through this system and use the energy created to partially power the breweries. Assuming Firestone Walker's annual growth rate of 25% remains accurate, in several years it may become practical for Firestone Walker to implement an anaerobic digester.

Conclusion

The knowledge of wastewater treatments gained from research and the opportunity to apply that knowledge towards a recommendation for Firestone Walker Brewing Company are two valuable skills that I am proud to have gained through this Senior Project. As mentioned in the Introduction, wastewater treatment will always be a challenge faced by every industry. My new skills and knowledge about wastewater treatment will hopefully allow me to lessen this challenge and increase the efficiency of future wastewater treatment systems I encounter.

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Appendices____

Appendix A: Facilities and Pretreatment Certification

Appendix B: Disinfection Certification

CALIFORNIA STATE UNIVERSITY, SACRAMENTO

OFFICE OF WATER PROGRAMS

College of Engineering and Computer Science

in Cooperation with the College of Continuing Education

This is to certify that

JESSICA UIBEL

Has completed a program in

Wastewater Treatment: Disinfection

Earning 1.8 CEUs, February 2015

422337

DEAN, COLLEGE OF CONTINUING EDUCATION

CALIFORNIA STATE UNIVERSITY, SACRAMENTO · 1947 ·

DIRECTOR, OFFICE OF WATER PROGRAMS

Appendix C: Recycled Water Uses Allowed in California

Recycled Water Uses Allowed[1] in California

Use of Recycled Water	Treatment Level: Disinfected Tertiary Recycled Water	Treatment Level: Disinfected Secondary – 2.2 Recycled Water	Treatment Level: Disinfected Secondary – 23 Recycled Water	Treatment Level: Undisinfected Secondary Recycled Water
Irrigation of:				
Food crops where recycled water contacts the edible portion of the crop, including all root crops	**Allowed**	Not Allowed	Not Allowed	Not Allowed
Parks and playgrounds	**Allowed**	Not Allowed	Not Allowed	Not Allowed
School yards	**Allowed**	Not Allowed	Not Allowed	Not Allowed
Residential landscaping	**Allowed**	Not Allowed	Not Allowed	Not Allowed
Unrestricted-access golf courses	**Allowed**	Not Allowed	Not Allowed	Not Allowed
Any other irrigation uses not prohibited by other provisions of the California Code of Regulations	**Allowed**	Not Allowed	Not Allowed	Not Allowed
Food crops, surface-irrigated, above-ground edible portion, and not contacted by recycled water	**Allowed**	**Allowed**	Not Allowed	Not Allowed
Cemeteries	**Allowed**	**Allowed**	**Allowed**	Not Allowed
Freeway landscaping	**Allowed**	**Allowed**	**Allowed**	Not Allowed
Restricted-access golf courses	**Allowed**	**Allowed**	**Allowed**	Not Allowed
Ornamental nursery stock and sod farms with unrestricted public access	**Allowed**	**Allowed**	**Allowed**	Not Allowed
Pasture for milk animals for human consumption	**Allowed**	**Allowed**	**Allowed**	Not Allowed
Non-edible vegetation with access control to prevent use as a park, playground or school yard	**Allowed**	**Allowed**	**Allowed**	Not Allowed
Orchards with no contact between edible portion and recycled water	**Allowed**	**Allowed**	Not Allowed[2]	Not Allowed[2]
Vineyards with no contact between edible portion and recycled water	**Allowed**	**Allowed**	Not Allowed[2]	Not Allowed[2]
Non food-bearing trees, including Christmas trees not irrigated less than 14 days before harvest	**Allowed**	**Allowed**	**Allowed**	**Allowed**
Fodder and fiber crops and pasture for animals not producing milk for human consumption	**Allowed**	**Allowed**	**Allowed**	**Allowed**
Seed crops not eaten by humans	**Allowed**	**Allowed**	**Allowed**	**Allowed**
Food crops undergoing commercial pathogen-destroying processing before consumption by humans	**Allowed**	**Allowed**	**Allowed**	**Allowed**
Ornamental nursery stock, sod farms not irrigated less than 14 day before harvest	**Allowed**	**Allowed**	**Allowed**	**Allowed**
Supply for impoundment:				
Non-restricted recreational impoundments, with supplemental monitoring for pathogenic organisms	**Allowed[3]**	Not Allowed	Not Allowed	Not Allowed
Restricted recreational impoundments and publicly-accessible fish hatcheries	**Allowed**	**Allowed**	Not Allowed	Not Allowed
Landscape impoundments without decorative fountains	**Allowed**	**Allowed**	**Allowed**	Not Allowed
Supply for cooling or air conditioning:				
Industrial or commercial cooling or air conditioning involving cooling tower, evaporative condenser, or spraying that creates a mist	**Allowed[4]**	Not Allowed	Not Allowed	Not Allowed
Industrial or commercial cooling or air conditioning not involving cooling tower, evaporative condenser, or spraying that creates a mist	**Allowed**	**Allowed**	**Allowed**	Not Allowed

Recycled Water Uses Allowed[1] in California

(continued)

Use of Recycled Water	Treatment Level: Disinfected Tertiary Recycled Water	Disinfected Secondary – 2.2 Recycled Water	Disinfected Secondary – 23 Recycled Water	Undisinfected Secondary Recycled Water
Other uses:				
Groundwater recharge	**Allowed** under special case-by-case permits by RWQCBs[5]			
Flushing toilets and urinals	**Allowed**	Not Allowed	Not Allowed	Not Allowed
Priming drain traps	**Allowed**	Not Allowed	Not Allowed	Not Allowed
Industrial process water that may contact workers	**Allowed**	Not Allowed	Not Allowed	Not Allowed
Structural fire fighting	**Allowed**	Not Allowed	Not Allowed	Not Allowed
Decorative fountains	**Allowed**	Not Allowed	Not Allowed	Not Allowed
Commercial laundries	**Allowed**	Not Allowed	Not Allowed	Not Allowed
Consolidation of backfill material around potable water pipelines	**Allowed**	Not Allowed	Not Allowed	Not Allowed
Artificial snow making for commercial outdoor uses	**Allowed**	Not Allowed	Not Allowed	Not Allowed
Commercial car washes, not heating the water, excluding the general public from washing process	**Allowed**	Not Allowed	Not Allowed	Not Allowed
Industrial process water that will not come into contact with workers	**Allowed**	**Allowed**	**Allowed**	Not Allowed
Industrial boiler feedwater	**Allowed**	**Allowed**	**Allowed**	Not Allowed
Non-structural fire fighting	**Allowed**	**Allowed**	**Allowed**	Not Allowed
Backfill consolidation around non-potable piping	**Allowed**	**Allowed**	**Allowed**	Not Allowed
Soil compaction	**Allowed**	**Allowed**	**Allowed**	Not Allowed
Mixing concrete	**Allowed**	**Allowed**	**Allowed**	Not Allowed
Dust control on roads and streets	**Allowed**	**Allowed**	**Allowed**	Not Allowed
Cleaning roads, sidewalks, and outdoor work areas	**Allowed**	**Allowed**	**Allowed**	Not Allowed
Flushing sanitary sewers	**Allowed**	**Allowed**	**Allowed**	**Allowed**

This summary is prepared from the December 2, 2000-adopted Title 22 Water Recycling Criteria and supersedes all earlier versions. Prepared by Bahman Sheikh and edited by EBMUD Office of Water Recycling, who acknowledge this is a summary and not the formal version of the regulations referenced above.

Appendix D: Firestone Walker Recommendation Report

Tertiary Wastewater Recommendation

A Senior Project presented to
Firestone Walker Brewing Company

By Jessica Uibel
Liberal Arts and Engineering Studies
March 2015

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Appendices

Executive Summary

In 2014, Firestone Walker began the implementation of an onsite Wastewater Treatment Plant to treat the brewery's process wastewater. Although the secondary treatment of aerated lagoons was capable of lowering the effluent to Paso Robles discharge requirements, Firestone Walker considered investing in a tertiary treatment to reclaim water for industrial reuse in wash down, evaporative coolers, and steam generation.

The information required to determine to optimal tertiary treatment system included the effluent levels leaving the lagoons, the influent requirements for the reclamation uses, the discharge requirements from Paso Robles, and the flow rate of the process wastewater. With this information, different filtration and disinfection systems were measured to determine the optimal treatment system to compliment the Nanofiltration system.

Overall, the recommended tertiary treatment is a Slow Sand Filtration system, followed by a Nanofiltration system, and ending with an Ultraviolet system. The combination of these three treatments should produce an effluent that matches the requirements set in the California Code of Regulations Title 22 for recycled water quality levels.

Slow Sand Filtration was chosen for its comparatively inexpensive capital cost, ease of maintenance, and avoidance of chemicals or backwashing. Nanofiltration was chosen for its specialization in lowering total hardness and its ability to use a lower feed pressure than Reverse Osmosis, resulting in lower energy requirements and higher permeate levels. Ultraviolet was chosen for its ability to disinfect most known pathogens without the creation of dangerous by-products or use of chemicals.

Each of the system capital costs are estimates that lay on the conservative side, and each will fluctuate depending on the actual flow rate of the system and quality of the effluent entering the system. However, the current estimated total capital cost is $353,250 with an estimated annual operations and maintenance cost of $32,440. Although the average Nanofiltration system can recover 85%-95% of the feed water, using a slightly lower recover rate of 80% results in a Return on Investment of 15.55 months. Again, as this number is highly uncertain and depends on actual capital cost and percentage of water reclaimed, an ROI Matrix was created to allow quick identification of possible ROI values once these values are known. So long as the expected annual growth rate remains at 25%, the information in the matrix will remain valid.

Should the recommendations in this report be considered for implementation, it is recommended that Firestone Walker contact Dr. Rebekah Oulton, at roulton@calpoly.edu, so that further design parameters can be analyzed.

System Requirements

Before considering the possible treatment systems, the system requirements needed to be defined to ensure that the goals of the tertiary treatment were being met. These requirements included determining (1) the effluent levels from Aerated Ponds, the step preceding the tertiary treatment, (2) the influent requirements for Evaporative Coolers, Wash Down, and Steam Generation, (3) the effluent levels to discharge to the city of Paso Robles, (4) the daily flow rate, and (5) the possible expansion needs.

Effluent levels from Aerated Ponds

Prior to entering the tertiary system, the water will have flown through the secondary treatment of aerated ponds and will be treated for BOD, pH, and TSS. As the aerated ponds were not fully operational by the time of this research, definite levels could not be determined. However, several texts and studies were consulted to reach an average value of the water levels seen from aerated pond effluents.

According to the text, "Wastewater Engineering: Treatment and Reuse," the minimum national standards for secondary treatments shown in Table 1 below:

Characteristic of Discharge	Unit of Measurement	Avg. 30 Day Concentration	Avg. 7 Day Concentration
BOD	mg/L	<30 (85% removal)	45
TSS	mg/L	<30 (85% removal)	45
Hydrogen Ion Concentration	pH Units	Between 6.0 – 9.0 at all times	
CBOD	mg/L	25	40

Table 1. Summary of the minimum national standards for secondary treatments for BOD, TSS, pH, and CBOD (Tchobanoglous, Burton, Stensel)

In addition to these national standards, the Environmental Protection Agency's article on Partial Mixed Aerated Lagoons further verified the effluent quality of the ponds, stating that "aerated lagoons can reliably produce an effluent with both BOD and TSS less than or equal to 30 mg/L if provisions for settling are included at the end of the system" ("Wastewater").

As aerated ponds are a secondary treatment, for the purposes of this project I am assuming that Firestone Walker will properly operate and maintain their treatment ponds to produce results consistent with the national standards.

Influent to Evaporative Coolers, Wash Down, and Steam Generation

For the tertiary system effluent, the receiving water requirements were found in the California Code of Regulations (CCR), Title 22 Social Security - Division 4 Environmental Health - Chapter 3 Water Recycling Criteria - Article 3 Uses of Recycled Water. A summary of the applicable regulations will be listed below, and the full section can be found in Appendix A. In addition to these regulation, Firestone Walker requested the influent has a low Total Hardness to reduce mineral buildup on pipes and plumbing.

Evaporative Coolers: Section 60306 - Use of Recycled Water for Cooling
Recycled water used for industrial or commercial cooling or air conditioning that involves the use of a cooling tower, evaporative condenser, spraying or any mechanism that creates a mist shall be a disinfected tertiary recycled water.

Wash Down: Section 60307 - Use of Recycled Water for Other Purposes
Recycled water used for the following shall be disinfected tertiary recycled water, except that for filtration being provided pursuant to Section 60301.320 (a) coagulation need not be used as part of the treatment process provided that the filter effluent turbidity does not exceed 2 NTU, the turbidity of the influent to the filters is continuously measured, the influent turbidity does not exceed 5 NTU for more than 15 minutes and never exceeds 10 NTU, and that there is the capability to automatically activate chemical addition or divert the wastewater should the filter influent turbidity exceed 5 NTU for more than 15 minutes.

Steam Generation: Section 60307 - Use of Recycled Water for Other Purposes
(b) Recycled water used for the following uses shall be at least disinfected secondary-23 recycled water:

The definitions of "filtered wastewater," "disinfected tertiary recycled water," and "disinfected secondary-23 recycled water" can be found in Appendix B. Table 2 summarizes the requirements for the three reuse purposes.

<table>
<tr><th>Reuse Purpose</th><th>CCR Requirements</th><th>Firestone Walker Requirements</th></tr>
<tr><td>Evaporative Coolers</td><td rowspan="2">Total Coliform Bacteria does not exceed an MPN of 2.2 ppm and sent through system that removes 99.999% of Polio Virus, turbidity does not exceed 0.2 NTU more than 5% of the time during a 24-hour period or 0.5 NTU at any time</td><td>Low Total Hardness</td></tr>
<tr><td>Wash Down</td><td>N/A</td></tr>
<tr><td>Steam Generation</td><td>Total Coliform Bacteria does not exceed an MPN of 23 ppm</td><td>Low Total Hardness</td></tr>
</table>

Table 2. Summary of the Influent Requirements set forth in the California Code of Regulations for the purposes of Evaporative Coolers, Wash Down, and Steam Generation

Effluent to City of Paso Robles

The concentrate from the Nanofiltration system will need to be tested for compliance with the Paso Robles discharge limits. These limits from the Municipal Code of Paso Robles can be found in Appendix C. For this project, the limits of the highest concern included the three limitations found in Table 3.

Constituent	Concentration Limits
Total Dissolved Solids (TDS)	1000 mg/L
Biochemical Oxygen Demand	360 mg/L
Total Suspended Solids	360 mg/L

Table 3. Concentration Limits taken from the El Paso De Robles Code of Ordinances - Title 14 Water and Sewers - Chapter 14.10 Discharge of Industrial (Non-Domestic Waste) - Article II Prohibitions and Limits on Discharges - Section 14.10.060 Local Limits, Parts A and B

Should the concentrate exceed any of these limits, it will need to be diluted before it can be discharged to the City of Paso Robles. The effluent from the aerated ponds would be an ideal candidate for the diluent since the TSS, TDS, and BOD levels should typically fall below 30 mg/L. However, the impact of using the pond effluent is that less water will flow through the tertiary treatment, resulting in a lowered total amount of reclaimed water.

Daily Flow Rate

According to the Firestone Walker Utility Bill Tracking Spreadsheet, the average 2014 monthly gallon usage was 2,713,079 gallons of water, resulting in a daily average usage of 89,558 gallons of water. This daily usage calculation was made by taking the monthly usage units, multiplying this number by 748 (to obtain the gallons used), and then dividing the resulting number by the appropriate amount of days per month. A table of this data can be found in Appendix D.

Possible Expansion Needs

By September of 2014, Firestone Walker had spent $191,571.40 on water. This amount is expected to rise approximately by 25% annually, resulting in the expected water consumption rates over the next five years (shown in Table 4).

Given the approximated growth rate of 25% is correct, the system will need the capability of processing twice the current flow rate to account for production through 2018, with the capabilities to double yet again to account for production growth future years.

Year	Annual Water Costs
2015	$319,285
2016	$399,107
2017	$498,883
2018	$623,604
2019	$779,506

Table 4. Predicted annual water costs through 2019

Decision Matrix for Considered Systems

The determine which systems to analyze, three filtration systems and three disinfection systems were measured against each other to find the optimal system for Firestone Walker. The filtration systems analyzed included membrane filters (ultrafiltration and microfiltration), rapid sand filtration, and slow sand filtration. The disinfection systems analyzed included chlorination, ultraviolet, and ozone.

Filtration Process

For the filtration process, the three systems that were evaluated were membrane filtration (Ultrafiltration and Microfiltration), Rapid Sand Filtration, and Slow Sand Filtration. The criteria the systems were judged against were (1) Capital Cost, (2) Operation and Maintenance, (3) Influent Water Quality, (4) Effluent Water Quality, (5) Area Requirements, (6) Chemical Requirements, (7) Energy Requirements, (8) Backwashing Requirements, and (9) Operator Skill Level Requirements.

Each criteria was ranked to be low, medium, or high, and the corresponding number (1, 3, or 5) was assigned based on the desired ranking of the criteria. The definition of low, medium, or high was determined by comparing the relative values of the criteria from several different sources. The scores for each criteria were then multiplied together, and the system with the lowest value was chosen as the recommended system. The information to populate this matrix was gathered from several sources, including the articles from Marco Bruni from the Sustainable Sanitation and Water Management and the text "Wastewater Engineering: Treatment and Reuse" by Metcalf and Eddy.

	Weight	Membrane Filtration	Rapid Sand Filtration	Slow Sand Filtration
Capital Cost	Low (1) : Cost is less than $1.00/gpd Medium (3) : Cost is between $1.00/gpd and $2.00/gpd High (5) : Cost is greater than $2.00/gpd	5	3	3
Operation and Maintenance	Low (1): Minimal maintenance Medium (3): Weekly maintenance High (5): Daily maintenance	1	3	1
Influent Water Quality	Low (1): Can treat water between 10 - 100 NTU Medium (3): Can treat water between 5 - 10 NTU High (5):Can treat water less than 5 NTU	1	1	5
Effluent Water Quality	Low (5): Effluent isn't sufficient for RO Medium (3): Effluent is sufficient, but method is not widely used High (1):Effluent is sufficient and method is widely used	1	3	1
Area Requirements	Low (1): System requires small footprint Medium (3): System requires medium footprint High (5): System requires large footprint	1	3	5
Chemical Requirements	Low (1): Little to no chemicals are used in the process Medium(3): Chemicals are frequently used to aid the process High(5): Chemicals are required for the process	3	3	1
Energy Requirements	Low(1): Requires little to no energy Medium(3): Requires some of energy to filter High(5): Constantly requires a high amount of energy to filter	5	5	1
Backwashing Requirements	Low(1): Requires little to no backwashing Medium(3): Requires weekly backwashing High(5): Requires daily backwashing	5	3	1
Operator Skill Level Requirements	Low (1): Operators need minimal training and expertise Medium (3): Operators need some higher training and expertise High (5): Operators need high level of training and expertise	3	5	1
Total Score		1125	18225	75

Table 5. Decision matrix outcomes for the comparison of filtration systems. The system with the lowest total score, Slow Sand Filtration, was recommended to be implemented.

Disinfection Process

For the disinfection process, the three systems that were evaluated were chlorination, ultraviolet, and ozone. The criteria the systems were judged against were (1) Capital Cost, (2) Operation and Maintenance, (3) Effluent Water Quality, (4) Area Requirements, (5) Energy Requirements, (6) Chemical Requirements, and (7) Operator Skill Level Requirements.

The matrix functions similarly to the matrix in Table 5. Each criteria was ranked to be low, medium, or high, and the corresponding number (1, 3, or 5) was assigned based on the desired ranking of the criteria. The definition of low, medium, or high was determined by comparing the relative values of the criteria from several different sources. The scores for each criteria were then multiplied together, and the system with the lowest value was chosen as the recommended system. The information to populate this matrix was gathered from several sources, including the articles from Marco Bruni from the Sustainable Sanitation and Water Management and the text "Wastewater Engineering: Treatment and Reuse" by Metcalf and Eddy.

	Weight	Chlorination	UV	Ozone
Capital Cost	Low (1): Cost is less than $10,000 Medium (3): Cost is between $10,000 and $25,000 High (5): Cost is greater than $25,000	1	3	5
Operation and Maintenance	Low (1): Minimal maintenance Medium (3): Weekly maintenance High (5): Daily maintenance	3	3	3
Effluent Water Quality	Low (5): Does not meet tertiary treatment requirements Medium (3): Meets most of the tertiary requirements High (1): Meets all of the tertiary requirements	1	1	1
Area Requirements	Low (1): System requires small footprint (comparatively) Medium (3): System requires medium footprint High (5): System requires large footprint	1	1	1
Energy Requirements	Low(1): Requires little to no energy to disinfect Medium(3): Requires some of energy to disinfect High(5): Constantly requires a high amount of energy to disinfect	3	3	5
Chemical Requirements	Low (1): Little to no chemicals are used in the process Medium (3): Chemicals are frequently used to aid the process High (5): Chemicals are required for the process	5	1	5
Operator Skill Level Requirements	Low (1): Operators need minimal training and expertise Medium (3): Operators need some higher training and expertise High (5): Operators need high level of training and expertise	1	1	3
Total Score		45	27	1125

Table 6. Decision matrix outcomes for the comparison of disinfection systems. The system with the lowest total score, Ultraviolet, was recommended to be implemented.

Recommended System

After defining the system requirements and measuring the criteria for each system, the lowest scoring systems were analyzed to determine the optimal system designs for Firestone Walker's process. The systems to be analyzed included slow sand filtration, nanofiltration, and ultraviolet. Each system is evaluated in terms of its cost, performance, and design.

Slow Sand Filtration

For the pre- nanofiltration step, Slow Sand Filtration (SSF) was chosen due to its low score in the Filtration Decision Matrix. The benefits of the SSF include its relative ease of maintenance, its high quality of effluent, and its use of gravity for filtration (no chemicals or energy needed). The downsides of SSF systems include its large area requirements and its specificity in influent water levels.

Costs

Estimated construction costs for a SFF system can vary significantly depending on the facility and flow rate, but a general, conservative estimation comes from the Washington State Department of Health report. In 2002, the cost curve placed a SFF system of Firestone Walker's size around $100,000. Using construction cost escalation from International Contractors Inc., we can expect about a 7% cost increase from this 2002 estimation. The final resulting cost would be around $107,000 (Selecky, White, and Grunenfelder).

Although it still has a large capital cost, a study performed by the US Interior Bureau of Reclamation found that "comparing unit costs, SSF, at $0.13 per thousand gallons, has less than one-fourth the cost of $0.57 per thousand gallons for conventional treatment or MF/UF." Additionally, the study found that the SSF-RO combination cost less than a MF/UF-RO combination by approximately $0.30 per thousand gallons (Moody, Garrett, and Holler).

The main operation costs occur from the need to clean the filter beds of the schmutzdecke. Otherwise, the system does not use chemicals, compressed air, mechanical stirring, or pressured water for backwashing, which results in a savings in fuel and electricity compared to other systems (Bruni).

Performance

SSF systems filter water by passing it through the biological layer, the schmutzdecke, which forms on the top layer of the sand. The microbes that made up the schmutzdecke are largely "predatory bacteria… [which] feed on water-borne microbes passing through the filter (Bruni). This layer is effective in removing particles and micro-organisms, but "does not reduce hardness or salinity (TDS) levels in the water." SSF systems are also effective in removing particles that foul RO equipment (Moody, Garrett, and Holler).

As far as the quality of water that can be expected in SSF system effluent, studies have shown that SSF filtered water can reliably produce effluent with less than 1 NTU. (Moody, Garrett, and Holler). These levels can be expected as long as the influent into the SSF system is less than 10 NTU, since water with high NTU levels can clog the fine sand at the top of the filter media.

To ensure consistent water quality, the schmutzdecke needs to be periodically removed, most likely by manual labor, to unclog the fine sand. "The length of time between cleanings can range from several weeks to a year, depending on the raw water quality." Cleanings will be triggered when the allowable head loss is observed ("Tech").

Design

When designing a Slow Sand Filtration System, the design parameters to consider include filtration rate, number of filter bins, and filter media. When design parameters specific to Firestone Walker's system were not possible due to necessity of experimenting with the factors, average parameters were given.

Filtration Rate: Looking at filtration rate can help determine the necessary size of the filter basins. According to the report by Selecky, White, and Grunenfelder, "design filtration rates typically range from 0.05 gpm/ft2 to 0.1 gpm/ft2, although rates as high as 0.15 gpm/ft2 may be tolerated for short periods during filter scraping" (Selecky, White, and Grunenfelder). Looking at a 25% annual growth rate from 2014, the information in Table 7 was calculated.

Year	2014	2015	2016	2017	2018	2019
Gallons per Minute	62.19	77.74	97.18	121.47	151.84	189.80
Square Footage Required (at a rate of .1 gpm)	621.94	777.42	971.77	1214.72	1518.40	1898.00

Table 7. Square Footage for SSF Basins dependent on .1 gallons per minute flow rate

To ensure the design of the Slow Sand Filters can accommodate growth through 2019, a total of 1,898 square feet are required for a flow rate of .1 gallons per minute through the Slow Sand Filters. However, if the flow rate were to be reduced to .05 gpm, the required square footage would double in size. The benefit of lowering the flow rate to .05 gpm is that "lower filtration rates may provide longer filter runs." (Selecky, White, and Grunenfelder).

Number of Basins: Since Slow Sand Filtration requires that a filter be off line for up to two weeks for scraping the Schmutzdecke and filter ripening, the system design will typically incorporate more than one filter basin (Selecky, White, and Grunenfelder). The World Health Organization determined the recommended number of filter basins depending on flow rate, as displayed in Table 8.

Flow Rate	Number of Filter Basins
Less than 450 gpm	2
450 – 900 gpm	3
900 – 1,400 gpm	4
1,400 – 2,100 gpm	5

Table 8. Recommended Number of Filter Basins per Flow Rate

To be conservative in the design and prepare for a possible 2019 flow rate of approximately 1900 gpm, it is recommended to install 5 filter basins. Each basin would need to be approximately 380 square feet, minimum. However, if only 4 filter basins are installed, each would need to be a minimum of 475 square feet. Additionally, these calculations are assuming a constant flow rate through the day. Recommendations may change if Firestone Walker discovers that the flow rate is not constant, and the maximum flow rate exceeds 2,100 gpm.

Filter Media: Three considerations with filter media include the type of media, layers of media, and depth of media. The general recommended for SSF systems is a conventional, mono-medium, downward (gravity) flow, system with a depth 760 mm. The size of the sand is measured in effective diameter, d_{10}, meaning that only 10% of particles will be small enough to pass through the medium. Although this diameter can range between .15mm - .40 mm, the optimal size will be found through experimentation (Huisman & Tchobanoglous, Burton, Stensel). Additionally, according to Dr. Huisman: "The grains of the bottom layer of gravel should have an effective diameter of at least twice the size of the openings into the drainage system. Each successive layer should be graded so that its smaller (d_{10}) particle diameters are not more than four times smaller than those of the layer immediately below. The uppermost later of gravel must be selected with a d_{10} value more than four times greater than the d_{15}, value of the courses filtration sand and less than four times greater than the d_{85}, value of the finest filtration sands."

Nanofiltration

The SSF system serves as a pre-filtration for the Nanofiltration (NF) system. NF is a form of Reverse Osmosis (RO) that is useful in softening hard water. The NF membranes are most effective in rejecting divalent including calcium, magnesium, and sulfate (Moody, Garrett, and Holler). The benefit of the NF system, compared to a RO system, is that the capital and operational costs are lower, but the system is still able to produce the required effluent levels. An RO system is better designed to remove sodium from water, but Firestone Walker's wastewater is not expected to have high sodium levels ("Membrane").

Cost

NF systems don't require the higher driving pressure seen in RO systems, "making NF a more economical alternative when primarily divalent ion removal is required" (Fravel). The costs associated with installing a Nanofiltration system were found from the Environmental Protection Agency; the full cost table can be found in Appendix E. Although the cost is just an estimate, and it is estimated for ground water rather than industrial process water, for the purposes of this project it serves as a conservative, general comparison for the total cost of installing a NF system at Firestone Walker. The cost will also fluctuate depending on the amount of membranes needed to achieve the desirable recovery rate.

The total capital costs for a system that is designed for .18 mgd is $223,250 and the annual Operation and Maintenance costs are estimated to be $29,539. For a complete list of the items included in this estimate, please consult Appendix E ("Technology").

Performance

As Nanofiltration uses the same technology as RO systems, only with a larger pore size, many of the same performance levels can be expected. The main difference is that NF systems are not designed to remove salts from water. NF systems will have a lower TDS rejection rate compared to RO, but higher total hardness rejection rates and permeate rates (Li, Levy, and Wang). NF membranes can provide a higher permeate rate (85%-95%) because the membranes allow for a higher water flux at a lower operating pressure (Izadpanah and Javidnia, "Nanofiltration").

Additionally, a study conducted in 1989 by Dr. Cluff reported on the use of SSF as a pretreatment for NF, and found the combination to be highly effective (Cluff). Several studies have been completed regarding NF effluent quality, and results show that the system is capable of reducing Total Hardness by 96%-98%, as well as reducing both TDS and electrical conductivity by 79%-89%, and (Izadpanah and Javidnia).

Design

Three of the most important design parameters needed are the flow rate, the design flux, and the active membrane surface area of the selected element. With these three parameters, the number of elements can be determined, which leads to the number of pressure vessels and stages. From there, the appropriate membrane can be considered.

When discussing RO systems, H2O Engineering took these factors into consideration and recommended using their E8-108K model. This model contained 15 membranes in a 3-2 array. For the purposes of this project, it is assumed that the NF system will have a similar arrangement to the RO system. It is also recommended to use a continuous system with spiral membranes. Spiral membranes allow for the "highest membrane packing area capability with the smallest footprint. Spiral elements are robust, energy efficient, and economical to operate." ("Membrane")

When considering the actual types of NF membranes, the two most common are cellulose acetate based and polyamide composites. A study completed by Lechevallier and Keung found that composite thin film membranes were more effective at removing microbes than the cellulose acetate membranes.

Ultraviolet

Following the NF system is the Ultraviolet (UV) System. The purpose of this system is to disinfect the water to achieve reuse water quality levels. The benefits of using a UV system, compared to chlorination, are that UV systems do not require the use of any chemicals, which eliminates the creation of harmful by-products and storage of chlorine. However, the system requires energy to ensure the UV light can reach the entirety of the water passing through the system.

Cost

An estimate from H2O engineering placed the capital costs of the UV system to be $20,000. However, with installation costs, this price would likely raise to approximately $23,000.

The O&M costs for a UV system were adapted from the Water Tech Guide: Volume 2 from the University of New Hampshire. As the estimates are from 2001, a 7% construction cost escalation from International Contractors Inc. was used to bring the estimate into 2015 costs. The average O&M costs were found to be $2,900 (“UV Costs”).

Performance

Exposing wastewater to UV light breaks down the DNA and RNA of micro-organisms, making them incapable of reproducing or infecting. Typically, to reach the California Code of Regulation Title 22 requirement, that Total Coliform Bacteria does not exceed an MPN of 2.2 ppm and that the system removes 99.999% of Polio Virus, Fecal Coliform kills of 2.7 – 2.9 log are necessary (O’Connor).

Generally, factors that can affect the quality of UV system effluent are UV transmittance, flow rate, and water quality parameters such as TSS, NTU, and total hardness. “A decrease in transmittance, an increase in flow, or an increase in concentration of the water quality parameters of concern will result in a lower applied UV dose and lower performance.” (Johns, Lichtwardt, Grundenman, and Gallegos).

Design

Some of the major design parameters for UV systems include the pressure of the system, intensity of the lights, number of banks, amount of lamps per bank, and length of the system. These parameters are determined from factors such as flow rate, UV transmittance levels, influent water quality, lamp arrangement, and required contact time. Many of these variables are site-specific, but general trends can be found in this section (O’Connor, “Wastewater”).

UV systems are classified by the pressure and intensity of the lamps. The three categories are 1) low pressure/low intensity, 2) low pressure/high intensity, and 3) medium pressure/high intensity. “The wastewater flow and characteristics affect the type of system that is selected” (Johns, Lichtwardt, Grundenman, and Gallegos).

When considering low pressure (LP) versus medium pressure (MP), it’s important to note that only one MP lamp is required to produce the equivalent output of several LP lamps, which affects replacement costs. Additionally, LP lamps have a higher sensitivity to temperature then MP lamps (“Wastewater”). But, LP lamps are considered monochromatic, as they are limited to a sign wavelength of 254 nm, which makes them a more consistent choice than the MP lamps (“UV disinfection”).

When considering light intensity, one important factor is the wavelength of the UV light. Disinfection is most effective with either UV-B or UV-C light, which corresponds to wavelengths of 200-300 nm. Several studies have found that the optimal wavelength for inactivating microorganisms is around 256 nm (“Ultraviolet”).

Another important factor in UV design is the dosing requirement. The dosing requirements depend on the pre-treatment of the influent, since the UV transmittance of this water will affect the performance of the UV system. After passing through a NF system, the water should have a UV transmittance value between 65%-90%, corresponding to a UV transmittance value of between 50%-80% (Boeker). However, many wastewater plants average 65% UVT ("Wastewater").

Depending on the use of the lights and the quality of the water, the average lamp will need to be cleaned (by wiping down the quartz sleeve) and replaced every 9-12 months. This replacement should be relatively simple and achievable by general maintenance staff ("UV Disinfection").

Return on Investment

Because of the difficulty in obtaining an accurate cost estimate for the system, a matrix was created to determine the Return on Investment for the tertiary treatment (Figure 1). The matrix is based off of an annual growth rate of 25% from the water usage tracked in the Firestone Walker Utility Tracking spreadsheet.

Initial costs estimates placed the system in the range of $355,000-$375,000 capital costs and 80%-85% water reclaimed, coordinating to an ROI of approximately 14.5 – 16.5 months. Details on this system cost can be found in Table 9.

Factor	Cost	Source
Slow Sand Filtration	$107,000	Research - WOH
Nanofiltration	$223,250	Research - EPA
UV	$23,000	H20 Engineering
Total	$353,250	

Table 9. General cost estimates for the tertiary system

This value does not include expected operation and maintenance costs such as filter replacement or labor to clean the SSF system or UV lamps. However, O&M costs for the NF system are estimated to be $29,539 per year, and for the UV system are estimated at $2,900 per year for a total of $32,439 per year.

Return on Investment Matrix

Capital Costs of Tertiary Treatment

Percentage of Water Reclaimed	250,000	275,000	300,000	325,000	350,000	375,000	400,000	425,000	450,000
50.0%	17.43	18.94	20.44	21.94	23.45	24.76	25.96	27.17	28.37
52.5%	16.72	18.15	19.58	21.01	22.44	23.88	25.31	26.19	27.34
55.0%	16.07	17.43	18.80	20.17	21.53	22.90	24.21	25.31	26.40
57.5%	15.47	16.78	18.09	19.39	20.70	22.01	23.32	24.50	25.54
60.0%	14.93	16.18	17.43	18.69	19.94	21.19	22.44	23.70	24.76
62.5%	14.43	15.63	16.83	18.03	19.24	20.44	21.64	22.85	24.04
65.0%	13.96	15.12	16.28	17.43	18.59	19.75	20.90	22.06	23.22
67.5%	13.54	14.65	15.76	16.88	17.99	19.10	20.22	21.33	22.44
70.0%	13.14	14.21	15.29	16.36	17.43	18.51	19.58	20.66	21.73
72.5%	12.77	13.80	14.84	15.88	16.92	17.95	18.99	20.03	21.06
75.0%	12.42	13.42	14.43	15.43	16.43	17.43	18.44	19.44	20.44
77.5%	12.10	13.07	14.04	15.01	15.98	16.96	17.92	18.89	19.86
80.0%	11.75	12.74	13.68	14.61	15.55	16.49	17.43	18.37	19.31
82.5%	11.39	12.42	13.33	14.24	15.16	16.07	16.98	17.89	18.80
85.0%	11.05	12.13	13.01	13.90	14.78	15.66	16.55	17.43	18.32
87.5%	10.74	11.81	12.71	13.57	14.43	15.29	16.14	17.00	17.86
90.0%	10.44	11.48	12.42	13.26	14.09	14.93	15.76	16.60	17.43
	By March 2016		By September 2016						

By September 2017

By March 2017

Figure 1. Return on Investment Matrix for Tertiary Treatment, based off of an annual growth rate of 25%.

Best Practices

To maximize the effectiveness of the reclaimed water, the following best practices, found from the Brewer's Association, are recommended for evaporative coolers and steam generation:

Evaporative Coolers

The Brewers Association had four recommendations for minimizing water used in evaporative coolers: (1) Maximize the cycles of concentration, as many systems only operate at two-four cycles, even though six cycles may be possible (2) routinely survey the coolers to inspect for leaks or water losses (3) promptly replace or repair poorly operating blowdown valves, and (4) ensure the make-up water tank is never overflowing ("Brewers").

Steam Generation

The Brewer's Association recommends maximizing steam generation by (1) routinely inspecting for leaks and promptly repairing any findings (2) properly insulating steam and condensate pipes to decrease steam requirements and heat loss (3) if possible to return condensate, ensuring the return in maximized and recovered for reuse.

For other best practices suggestions, consult the Brewers Association Water and Wastewater: Treatment/Volume Reduction Manual.

Appendices

Appendix A: Title 22 Regulations

California Code of Regulations, Title 22 Social Security - Division 4 Environmental Health - Chapter 3 Water Recycling Criteria - Article 3 Uses of Recycled Water - Section 60306 Use of Recycled Water for Cooling

(a) Recycled water used for industrial or commercial cooling or air conditioning that involves the use of a cooling tower, evaporative condenser, spraying or any mechanism that creates a mist shall be a disinfected tertiary recycled water.
(b) Use of recycled water for industrial or commercial cooling or air conditioning that does not involve the use of a cooling tower, evaporative condenser, spraying, or any mechanism that creates a mist shall be at least disinfected secondary-23 recycled water.
(c) Whenever a cooling system, using recycled water in conjunction with an air conditioning facility, utilizes a cooling tower or otherwise creates a mist that could come into contact with employees or members of the public, the cooling system shall comply with the following:
  (1) A drift eliminator shall be used whenever the cooling system is in operation.
  (2) A chlorine, or other, biocide shall be used to treat the cooling system recirculating water to minimize the growth of Legionella and other micro-organisms.

California Code of Regulations, Title 22 Social Security - Division 4 Environmental Health - Chapter 3 Water Recycling Criteria - Article 3 Uses of Recycled Water - Section 60307 Use of Recycled Water for Other Purposes

Recycled water used for the following shall be disinfected tertiary recycled water, except that for filtration being provided pursuant to Section 60301.320 (a) coagulation need not be used as part of the treatment process provided that the filter effluent turbidity does not exceed 2 NTU, the turbidity of the influent to the filters is continuously measured, the influent turbidity does not exceed 5 NTU for more than 15 minutes and never exceeds 10 NTU, and that there is the capability to automatically activate chemical addition or divert the wastewater should the filter influent turbidity exceed 5 NTU for more than 15 minutes:

(1) Flushing toilets and urinals,
(2) Priming drain traps,
(3) Industrial process water that may come into contact with workers,
(4) Structural firefighting,
(5) Decorative fountains,
(6) Commercial laundries,
(7) Consolidation of backfill around potable water pipelines,
(8) Artificial snow making for commercial outdoor use, and

(9) Commercial car washes, including hand washes if the recycled water is not heated, where the general public is excluded from the washing process.

(b) Recycled water used for the following uses shall be at least disinfected secondary-23 recycled water:

(1) Industrial boiler feed,
(2) Nonstructural firefighting,
(3) Backfill consolidation around nonpotable piping,
(4) Soil compaction,
(5) Mixing concrete,
(6) Dust control on roads and streets,
(7) Cleaning roads, sidewalks and outdoor work areas and
(8) Industrial process water that will not come into contact with workers.

(c) Recycled water used for flushing sanitary sewers shall be at least undisinfected secondary recycled water.

Appendix B: Title 22 Definitions

§ 60301.320. Filtered Wastewater

"Filtered wastewater" means an oxidized wastewater that meets the criteria in subsection (a) or (b):

(a) Has been coagulated and passed through natural undisturbed soils or a bed of filter media pursuant to the following:

(1) At a rate that does not exceed 5 gallons per minute per square foot of surface area in mono, dual or mixed media gravity, up flow or pressure filtration systems, or does not exceed 2 gallons per minute per square foot of surface area in traveling bridge automatic backwash filters; and

(2) So that the turbidity of the filtered wastewater does not exceed any of the following:

(A) An average of 2 NTU within a 24-hour period;
(B) 5 NTU more than 5 percent of the time within a 24-hour period; and
(C) 10 NTU at any time.

(b) Has been passed through a microfiltration, ultrafiltration, nanofiltration, or reverse osmosis membrane so that the turbidity of the filtered wastewater does not exceed any of the following:

(1) 0.2 NTU more than 5 percent of the time within a 24-hour period; and
(2) 0.5 NTU at any time

§ 60301.225. Disinfected Secondary-23 Recycled Water

“Disinfected secondary-23 recycled water” means recycled water that has been oxidized and disinfected so that the median concentration of total coliform bacteria in the disinfected effluent does not exceed a most probable number (MPN) of 23 per 100 milliliters utilizing the bacteriological results of the last seven days for which analyses have been completed, and the number of total coliform bacteria does not exceed an MPN of 240 per 100 milliliters in more than one sample in any 30 day period.

§ 60301.230. Disinfected Tertiary Recycled Water

"Disinfected tertiary recycled water" means a filtered and subsequently disinfected wastewater that meets the following criteria:

(a) The filtered wastewater has been disinfected by either:

  (1) A chlorine disinfection process following filtration that provides a CT (the product of total chlorine residual and modal contact time measured at the same point) value of not less than 450 milligram-minutes per liter at all times with a modal contact time of at least 90 minutes, based on peak dry weather design flow; or

  (2) A disinfection process that, when combined with the filtration process, has been demonstrated to inactivate and/or remove 99.999 percent of the plaque-forming units of F-specific bacteriophage MS2, or polio virus in the wastewater. A virus that is at least as resistant to disinfection as polio virus may be used for purposes of the demonstration.

(b) The median concentration of total coliform bacteria measured in the disinfected effluent does not exceed an MPN of 2.2 per 100 milliliters utilizing the bacteriological results of the last seven days for which analyses have been completed and the number of total coliform bacteria does not exceed an MPN of 23 per 100 milliliters in more than one sample in any 30 day period. No sample shall exceed an MPN of 240 total coliform bacteria per 100 milliliters.

Appendix C: Paso Robles Municipal Code

El Paso De Robles Code of Ordinances - Title 14 Water and Sewers - Chapter 14.10 Discharge of Industrial (Non-Domestic Waste) - Article II Prohibitions and Limits on Discharges - Section 14.10.060 Local Limits, Parts A and B

Constituent	Concentration Limit		Constituent	Concentration Limit
Ammonia	20.0 mg/L		Zinc	4.00 mg/L
Boron	5.00 mg/L		Sulfate	200 mg/L
Cadmium	0.10 mg/L		Total Dissolved Solids (TDS)	1000 mg/L
Chromium	3.70 mg/L		Sodium	200 mg/L
Copper	0.30 mg/L		Chloride	150 mg/L
Cyanide	0.01 mg/L		Biochemical Oxygen Demand	360 mg/L
Nickle	1.90 mg/L		Total Suspended Solids	360 mg/L
Molybdenum	1.10 mg/L		Oil and Grease	100 mg/L
Selenium	0.27 mg/L			

Appendix D: Flow Rates

Monthly/Daily Water Usage 2014					
Month	Usage Units	Usage Gallons	Usage BBL	Usage Daily	Cost
January	3342	2499816.0	80639.2	80639.23	$ 19,223.40
February	3637	2720476.0	87757.3	97159.86	$ 20,919.70
March	3257	2436236.0	78588.3	78588.26	$ 18,736.10
April	3711	2775828.0	89542.8	92527.60	$ 21,344.70
May	3512	2626976.0	84741.2	84741.16	$ 20,203.40
June	4069	3043612.0	98181.0	101453.73	$ 23,403.70
July	4202	3143096.0	101390.2	101390.19	$ 25,608.50
August	3556	2659888.0	85802.8	85802.84	$ 21,668.50
September	3358	2511784.0	81025.3	83726.13	$ 20,463.40
October	0	0.0	0.0	-	$ -
November	0	0.0	0.0	-	$ -
December	0	0.0	0.0	-	$ -
Total	32644	24417712.0	787668.1	806029.00	$ 191,571.40
Average	3627.11	2713079.11	87518.68	89558.78	21285.71

Appendix E: Sand Filtration Cost Table

Exhibit 3.31 Estimated Costs for Nanofiltration Systems *(continued)*

Design Flow, mgd	0.007	0.022	0.037	0.091	0.18	0.27	0.36	0.68	1	1.2
Average Flow, mgd	0.0015	0.0054	0.0095	0.025	0.054	0.084	0.11	0.23	0.35	0.41
Unit Capital Cost Summary										
Total Unit Capital Cost	**$52,107**	**$69,454**	**$86,801**	**$156,293**	**$223,250**	**$316,569**	**$357,931**	**$664,969**	**$914,766**	**$1,083,344**
Indirect Capital Costs	$9,461	$9,801	$10,141	$11,606	$27,544	$35,829	$43,177	$71,730	$140,830	$156,348
Piloting	$1,000	$1,000	$1,000	$1,000	$10,000	$10,000	$10,000	$10,000	$60,000	$60,000
Permitting	$2,500	$2,500	$2,500	$2,599	$3,516	$5,043	$5,654	$10,657	$13,903	$16,653
Land	$853	$1,193	$1,533	$2,894	$3,914	$5,615	$6,295	$11,865	$7,739	$9,270
Operator Training	$0	$0	$0	$0	$0	$0	$1,000	$1,000	$3,000	$3,000
Housing	$5,108	$5,108	$5,108	$5,113	$10,114	$15,171	$20,228	$38,208	$56,188	$67,426
Capital Cost After Multiplier	$42,646	$59,653	$76,660	$144,687	$195,707	$280,740	$314,754	$593,239	$773,935	$926,996
Subtotal Process Cost	$25,537	$35,720	$45,904	$86,639	$117,190	$168,108	$188,475	$355,233	$463,434	$555,087
Subtotal NF Equipment Cost	$20,677	$31,016	$41,355	$82,710	$113,726	$165,420	$186,097	$355,394	$465,244	$558,292
Pipes and Valves	$2,068	$3,102	$4,135	$8,271	$11,373	$16,542	$18,610	$35,539	$46,524	$55,829
Instrumentation and Controls	$4,135	$6,203	$8,271	$16,542	$22,745	$33,084	$37,219	$71,079	$93,049	$111,658
Cartridge Prefiltration	$1,654	$2,481	$3,308	$6,617	$9,098	$13,234	$14,888	$28,432	$37,219	$44,663
Acid and Anti-Scalent Feed Systems	$620	$930	$1,241	$2,481	$3,412	$4,963	$5,583	$10,662	$13,957	$16,749
System Feed Pumps	$2,585	$3,877	$5,169	$10,339	$14,216	$20,677	$23,262	$44,424	$58,155	$69,787
Nanofilter Membrane Elements	$4,135	$6,203	$8,271	$16,542	$22,745	$33,084	$37,219	$71,079	$93,049	$111,658
Membrane Skid with Filter Housing	$4,135	$6,203	$8,271	$16,542	$22,745	$33,084	$37,219	$71,079	$93,049	$111,658
Clean-In-Place (CIP) System	$1,034	$1,551	$2,068	$4,135	$5,686	$8,271	$9,305	$17,770	$23,262	$27,915
Online Conductivity/pH and Turbidity Meters	$5,169	$5,169	$5,169	$5,169	$5,169	$5,169	$5,169	$5,169	$5,169	$5,169
Brine Discharge Pump (Not Included)	$258	$388	$517	$1,034	$1,422	$2,068	$2,326	$4,442	$5,816	$6,979
Annual O&M Summary										
Total Annual O&M Cost	**$6,909**	**$7,937**	**$9,025**	**$13,703**	**$29,539**	**$37,904**	**$43,223**	**$70,725**	**$112,309**	**$126,572**
Acid, Anti-Scalant, Caustic Chemicals	$50	$79	$139	$365	$788	$1,226	$1,606	$3,358	$3,832	$4,489
Clean-in-Place Chemicals	$50	$50	$50	$91	$197	$307	$401	$839	$1,277	$1,496
NF Membrane Replacement	$827	$1,241	$1,654	$3,308	$4,549	$6,617	$7,444	$14,216	$18,610	$22,332
Cartridge Filter Replacement	$30	$30	$30	$30	$39	$61	$80	$168	$2,555	$2,993
Repair, Maintenance and Replacement	$100	$100	$100	$100	$197	$307	$401	$839	$1,277	$1,496
Process Monitoring (HPCs)	$1,167	$1,167	$1,167	$1,253	$1,253	$1,338	$1,338	$1,338	$1,338	$1,338
Power	$75	$270	$474	$1,248	$2,696	$4,194	$5,493	$11,484	$17,476	$20,472
Labor	$4,460	$4,460	$4,460	$4,803	$14,408	$15,438	$15,438	$15,438	$30,876	$30,876
Surcharge for Brine Discharge (Sewer/Storm Drain/Brine Interceptor)	$150	$541	$952	$2,505	$5,410	$8,416	$11,021	$23,044	$35,067	$41,079

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