WHEY TO REACT

TEAM 9
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ENGR-339 SENIOR DESIGN PROJECT
CALVIN COLLEGE
14 DECEMBER 2012
Executive Summary:

Whey To React has partnered with the City of Wyoming Clean Water Plant (CWP) and Country Fresh LLC to determine the feasibility of fermenting the dairy waste product whey to stabilize the CWP’s phosphorus removal process. The CWP currently uses a biological phosphorus removal process (Bio-P) to remove phosphorus, which is in the form of orthophosphate ($\text{PO}_4^{3-}$), from the wastewater. When Bio-P fails, ferric iron phosphorus removal must be used. This is expensive. Whey To React’s project involved determining a process to produce volatile fatty acids (VFAs) from whey and using the VFAs produced to stabilize the Bio-P process and remove the need for expensive and complicated chemical remediation.

Currently, Country Fresh LLC pays for the whey to be added to hog feed at a local farm. Whey To React hopes to benefit both the CWP and Country Fresh through its work. Stabilizing the CWP’s Bio-P process with VFAs from whey while simultaneously saving Country Fresh money on whey transportation costs will accomplish this.

The optimal mass ratio of VFAs to $\text{PO}_4^{3-}$ for Bio-P to take place ranges between 7:1 and 10:1, with the best possible ratio at 8:1. Since the CWP Bio-P process works most of the time, the additional VFAs from the fermented whey would increase this VFA:PO4 ratio during the points of lowest VFA concentration. At the lowest point over the last five months, the VFA:PO4 ratio was only 6.6:1, which was not enough for successful Bio-P removal.

Whey To React has not yet performed a fermentation experiment to determine VFA content of Country Fresh’s whey after fermentation, but used the results from a very similar experiment reported in the literature to perform calculations. Whey To React plans on performing a whey fermentation experiment of its own during Calvin College’s Interim term. Also, all calculations were performed under the assumption that Country Fresh removed 90% of the phosphorus from its whey before transporting it to the CWP.

Along with determining the amount of VFAs that could be produced and assessing their usefulness, Whey To React also determined the optimal set-up for the whey’s path from its storage at Country Fresh to its introduction in the CWP’s anaerobic zone of the aeration tanks. Whey is transported from Country Fresh to the CWP by truck. From there, the truck delivers the whey (approximately 25,000 gallons per day, seven days a week) into a 30,000 gallon storage tank, located in the underground pipe gallery in the CWP’s basement. The whey is then pumped at five gallons per minute (GPM) into a 30,000 gallon anaerobic digester, where it ferments under continuous flow conditions. An external heat exchanger keeps the whey at 99 °F inside the anaerobic digester, allowing it to ferment faster. Recirculation pumps keep the whey well-mixed for optimal fermentation. Biogas produced by fermentation would be collected from the top of the digester, and piped to the odor control building for processing. The fermented whey, which would on average have fermented for one day, would be pumped at a rate of 17.4 GPM from the anaerobic digester to the anaerobic zone of the aeration basin, where the VFAs would aid in $\text{PO}_4^{3-}$ removal.
Calculations based on results from the experiment by Morales et al revealed that 454 kg/day of VFAs could be generated using this method of fermentation. This is enough to raise the 6.6:1 VFA/PO₄³⁻ ratio at its lowest point up to 7.9:1, just below optimal level of 8:1.

The team’s budget for this investigative project was zero dollars, as everything needed was provided by either the CWP, Country Fresh, or Calvin College. The budget for this project to be carried out, however, was found to be very close to $500,000 in upfront costs plus an annual cost of $75,000, as shown in Table 1.

### Table 1. Project budget

<table>
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<th>Transportation</th>
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<td>Total System</td>
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Total: $496,316.00 $74,478.00

Whey To React will conduct an experiment in January to determine optimal temperature and retention time for VFA production. Based on the results of that experiment, a fermenter producing 468 kilograms of VFAs per day will be designed, allowing the CWP’s Bio-P to achieve an 8:1 VFA: PO₄³⁻ ratio. Whey To React will also design a storage tank and the plumbing necessary to integrate all parts into the existing plant. A final design report will be prepared and the results presented at Senior Design Night.
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Van.................................................................................................................................................

Fuller...............................................................................................................................................
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1 Introduction

1.1 Senior Design

Senior Design is the capstone course for the engineering major at Calvin College. In addition to career related lectures, the course challenges students to apply what they have learned and take ownership of a unique project. Senior Design facilitates a transition from student to practicing engineer by challenging students to produce solutions to real life problems without intermediate deadlines from professors and teaching them how to approach a problem previously unconsidered, both skills necessary for real world engineering projects.

As a Christian team at a Christian school, Whey To React believes engineers must use their talents in a God-pleasing way. Whey To React’s unique set of skills require a specific life purpose; ignoring that purpose dishonors the Maker who gave us those skills. In the words of track legend Steve Prefontaine, “To give anything less than your best is to sacrifice the gift.”

2 The Team

From left to right: Eric La Reau, Chad Van Soelen, Michael Fuller, Greg Whittle
2.1 Michael Fuller

Michael Fuller will graduate with a B.S.E, Civil & Environmental Concentration. A native Ohioan, he spent last summer performing research with Dr. David Wunder, analyzing and optimizing a point-of-use water filter’s ability to remove contaminants from drinking water. He has played on the baseball team and in the Pep Band for four years, graded papers in the math department for three years, and earned recognition in Calvin’s Big Idea Competition one year. He plans to study urban planning at a graduate school to be determined.

2.2 Eric La Reau

Eric LaReau will be graduating with a B.S.E. with a Civil & Environmental Concentration. He grew up in Lansing, Illinois, just south of Chicago. Eric worked for Progressive AE and Moore & Bruggink Inc. Consulting Engineers, where surveyed bus stop locations and inspected water mains and road work among other responsibilities. Eric is also a member of the American Society of Civil Engineers (ASCE). He enjoys spending quality time with his family and watching Chicago sports. After graduation, Eric hopes to join the civil engineering work force.

2.3 Chad Van Soelen

Chad Van Soelen will be graduating with a B.S.E with a Civil & Environmental Concentration. He grew up in Byron Center just south of Grand Rapids, Michigan. Chad has worked for Louis Padnos Iron & Metal Company and Progressive AE, but currently works at Holland Engineering. He has enjoyed the variety of internships he has experienced over the past 3 years, performing such tasks as observing site development, analyzing ADA regulations for bus stops, and currently participating in natural gas and petroleum pipeline design. When Chad is not busy with school or work he enjoys being a member of the ASCE, water skiing, and snowboarding. After graduation, Chad will be entering the civil engineering work force.

2.4 Greg Whittle

Greg Whittle will be graduating with a B.S.E. with a Civil & Environmental Concentration. He grew up in Galesburg, Illinois, but it’s been said that his heart lies in the great state of Michigan. Greg worked for the City of Wyoming Public Works last summer, where he gathered valuable experience performing a wide variety of tasks, including site plan editing, designing of structures, Graphical Information Systems (GIS) projects, and scanning massive quantities of past engineering reports. There he enjoyed his job more than enough to confirm a career in the Civil & Environmental field, and hopes to eventually practice hydraulic or environmental engineering. Greg also runs Cross Country and Track & Field for Calvin, and is a practicing member of ASCE. Greg is looking towards entering the civil engineering work force directly out of Calvin, with a possibility of graduate school in the future.

3 Project Management

3.1 Problem Statement

The purpose of this project is to create a preliminary design for a fermentation reactor and all the necessary connective structures at the Wyoming Clean Water Plant in Wyoming, Michigan. This
reactor will store and ferment the whey, producing enough volatile fatty acids (VFAs) to stabilize the Bio-P process at the CWP. The design will include transporting whey to the CWP and integrating the reactor into the current CWP.

3.2 Project Definition

The City of Wyoming CWP currently has a Bio-P process in place, which is used to meet phosphorus removal standards. However, this process is a bit unstable, due to a shortage of VFAs in the system. Whenever a severe shortage occurs in which Bio-P is unable to occur, the CWP uses ferric iron to remove phosphorus from the wastewater. Chemical remediation is expensive, complicated, and not as environmentally sensitive as Bio-P removal. For this reason, the City of Wyoming would like to transition to a fully Bio-P process with no need for ferric chloride removal.

As shown in Figure 1 below, Country Fresh LLC is located approximately 5 miles from the CWP. The dairy produces 175,000 gallons of whey per week, which cannot be disposed of down a drain due to its high Biological Oxygen Demand (BOD₅) and phosphorus content (in the form of orthophosphates, PO₄³⁻). The current protocol for dealing with the whey byproduct consists of paying hog farmers to turn it into hog feed; however, the whey’s high lactic acid content favors fermentation to create VFA’s, such as acetic and propionic acid.

![Figure 1. Map showing location of the CWP (A) and Country Fresh (B) (maps.google.com)](image)

Whey To React designed a method of dealing with the whey byproduct that could benefit both the CWP and Country Fresh. This involved designing the entire process that the whey would travel along from the moment it leaves Country Fresh to the moment it is injected into the CWP’s treatment system. This included transporting the whey from Country Fresh to the CWP, storing it during fermentation, and integrating it into the existing CWP.
3.3 Background

3.3.1 City of Wyoming

The City of Wyoming is located in Kent County, in southwestern Michigan, as shown in Figure 2 below. The largest suburb of Grand Rapids, Michigan, it is also the fourteenth largest city in Michigan with a total population of 72,125, according to a 2010 census.

3.3.2 Country Fresh

Country Fresh is a national company, owned by Dean Foods, which produces a variety of dairy products, including milk and cream, cottage cheese, half and half, eggnog, juices, ice cream, sherbet and other frozen desserts. Country Fresh also includes the brands Stroh’s, TruMoo, Swiss, and Fruit Rush. Examples of their dairy products can be seen in Figure 3. Founded in 1946, in Grand Rapids, Michigan, Country Fresh started out serving only 43 customers, and takes pride in not only delivering the best conventional dairy products, but in creating new products and developing new goods for its now many customers. Ideas such as the half-gallon ice cream container originated with Country Fresh, and continue to be a popular item today.
3.3.3 Wastewater Treatment Overview

Conventional wastewater treatment consists of four main treatment phases: preliminary treatment, primary treatment, secondary treatment, and tertiary treatment (Figure 4).

- Preliminary treatment removes the largest and fastest-settling particles in order to protect the equipment and capacity downstream in the treatment process.
- Primary treatment removes 60% of particles and 30% of BOD$_5$ through settling in order to reduce the waste load. Settled particles, viz. non-biological sludge, are processed via “sludge management.”
- Secondary treatment employs bioreactors and clarifiers to remove 90-95% of the remaining BOD$_5$ and all remaining total suspended solids (TSS) in order to reduce the waste load. Settled particles, viz. waste-activated sludge (WAS), are also processed through sludge management.
- Tertiary treatment filters sand, anthracite, TSS, phosphorus, nitrogen, BOD$_5$, and biological particles from the waste stream.
- Disinfection prepares the water for discharge into a nearby water source using either chlorine or ultraviolet light.
- Sludge management involves removing water from sludge, converting the sludge to non-pathogenic material, removing more water, and either delivering it to a landfill, burning it, or applying it as fertilizer.
3.3.4 City of Wyoming Clean Water Plant

The City of Wyoming Clean Water Plant (CWP) is a wastewater treatment plant located in Wyoming, Michigan, which has a capacity of 24 million gallons of wastewater per day (MGD). As shown in Figure 5, the CWP treats 15 MGD on average.
The highest monthly flow over the past three years is 18.9 MGD (Table 2). Wyoming CWP treats wastewater for the 140,000 people in Wyoming and its four surrounding communities, discharging into the Grand River and recovering solids for fertilizer.

Table 2. Influent flow content for City of Wyoming CWP

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<th></th>
<th>2010</th>
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<th>2012</th>
<th>3-Year Average</th>
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<td><strong>Max Monthly Flow (MGD)</strong></td>
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<td><strong>BOD (mg/L)</strong></td>
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<tr>
<td><strong>TSS (lb./day)</strong></td>
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<td>234.8</td>
<td>244.4</td>
<td>241.1</td>
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<td><strong>Phosphorus (mg/L)</strong></td>
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<td><strong>NH3 (mg/L)</strong></td>
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<td>64.1</td>
<td>61.9</td>
<td>63.8</td>
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</table>
Whey To React’s project will focus on the secondary treatment phase of the CWP, which is the phase that currently removes phosphorus from the wastewater. Effluent standards for the CWP can be viewed in Appendix A.

### 3.3.5 Biological Phosphorus Removal

CWP’s secondary treatment phase consists of five main stages: the preanoxic stage, anaerobic stage, aerobic stage, clarifier, and return activated sludge (RAS). The effluent flow from the primary treatment is split up into two different flows, one which contains 80%, and the other 20%. The larger flow goes into the preanoxic stage, where the wastewater undergoes denitrification. From there it travels to the anaerobic zone, where it mixes with the rest of the primary effluent.

In the anaerobic phase, aerobic organisms known as phosphorus accumulating organisms (PAOs) consume VFAs, and due to the oxygen-free environment, are not able to respire as they normally would. The only source of oxygen available to the PAOs is that bonded with the phosphorus in the form of orthophosphates ($\text{PO}_4^{3-}$). The PAOs strip the oxygen from the phosphorus, ingest the oxygen, and discard the phosphorus. By the time the PAOs have ingested most of the oxygen bonded with the phosphorus, the wastewater stream has moved on the aerobic stage of the secondary treatment phase.

During the aerobic phase, these PAOs have more than enough oxygen to respire as they normally would, and have no need to seek oxygen by stripping it from the orthophosphates. The PAOs are then free to intake the phosphorus, and bond them with both hydrogen and oxygen, forming $\text{H}_2\text{PO}_4^-$. In the aerobic phase, more phosphorus is bonded with hydrogen and oxygen than is released during the anaerobic stage, resulting in a net phosphorus removal. For the Bio-P process to be successful, a VFA:PO4 mass ratio of between 7:1 and 10:1 is optimal. From the aerobic stage, the wastewater goes on to the clarifier.

The clarifier’s main purpose, as in any wastewater treatment, is to remove and dewater any solids that are still in the system. The solids are taken on two different paths from the clarifier. Around 60% of the clarifier’s total flow is recycled back into the system as recycled activated sludge (RAS). Of this RAS flow, 80% is injected into the preanoxic stage, while the remaining 20% goes into the anaerobic stage. This RAS contains PAOs, which are necessary for the Bio-P process to function. The solids which are not selected for the RAS stream are taken away as waste bacteria, and used as fertilizer. A third stream of water leaves the clarifier and is removed for further treatment.
The City of Wyoming CWP currently removes phosphorus using the Bio-P process, but as shown in Figure 8, high phosphorus levels or low levels of VFAs occasionally mandate the use of ferric iron.
3.4 Team Organization

Whey To React divided the work into two parts: Chad and Eric worked on the transportation and tank integration while Greg and Michael focused on the chemical and Bio-P processes. Whey To React met for an hour once per week to discuss last week’s progress, next week’s docket, and long-term goals. They also met with Dr. David Q. Wunder, who kept the project focused on the necessary topics and directed Whey to React to helpful resources. Whey To React also maintained correspondence with CWP personnel—Myron Erickson, Aaron Vis, and John Burke—for pertinent data and information.

3.5 Schedule

The team organized its duties and deadlines on the white board provided by the engineering department. Additionally, each team member tracked hours worked and tasks completed in a spreadsheet. During each meeting, urgent tasks were discussed and overall progress was evaluated. This method helped team members understand how the weekly tasks contributed to the end goal. Each team member averaged 6-8 hours per week towards the beginning of the semester, and as the project progressed, this number increased, with team members peaking at around 30-40 hours per week at the end of the semester. A detailed schedule is available in Appendix B.

3.6 Method of Approach

Before significant progress could be made, two main topics required extensive research: whey fermentation and biological phosphorus removal. Chad and Eric researched the whey fermentation process, while Greg and Mike investigated biological phosphorus removal.

Initial research built a foundation of general knowledge on the respective topics. Each pair researched their specific topic and taught it to the other pair. The long term value of this decision outweighed the initial difficulty. Again, group meetings were essential to communicating project information to other members of Whey To React, and weekly meetings with Professor Wunder kept the team looking for the right information. Journal articles, textbooks, and visits to the CWP provided the necessary knowledge base from which to work.

The research then became more specific, focusing on case studies of Bio-P removal and whey fermentation experiments. From this research, Whey To React understood what information was needed from the CWP. The CWP provided Whey To React enough information to do basic feasibility calculations. Eric and Chad looked into the process of transporting the whey and integrating it into the existing system, while Greg and Mike calculated VFA and phosphorus concentrations both in the whey and at certain points throughout the secondary treatment process. A fermentation experiment was modeled after the 2006 experiment by Morales et al., but the whey sample was received too late in the semester to conduct it. Feasibility calculations are based on values reported in the literature rather than empirical study, but an experiment will be performed over interim and included in final design considerations.
3.7 Design Norms

Design decisions for Whey To React are guided by stewardship, caring, and trust. Using whey to stabilize a wastewater treatment process uses resources in a more responsible and intentional manner. And that is important because every life choice has a consequence, so by making conscious choices, we can at least say we did everything we could to protect what we thought was important. When designing a fermenter for a system that serves 140,000 people, those consequences are magnified. We have to care as much about them as we do ourselves.

The design norm of trust factors into the potential partnership between the City of Wyoming CWP and Country Fresh. The relationship established between the public and private sectors requires that both parties can depend on our design.
# 4 Case Study Findings

The key findings of Whey To React’s research are summarized in Table 3.

<table>
<thead>
<tr>
<th>Study</th>
<th>Experimental Approach</th>
<th>Key Findings</th>
<th>Connection to Project</th>
</tr>
</thead>
</table>
| Morales et al.     | Inhibit acetic acid production with inhibitors during whey fermentation                | Average rate constants for acetic and propionic acid with and without inhibitors; retention time for peak VFA production | • Experiment modeled after this study  
• Lactic acid decomposition equation provided basis for feasibility calculations  
• Provided retention times for optimal VFA production - 35 hours at 30°C |
| Yang               | Measure propionic acid production from batch fermentation, continuous fermentation, and De-Lac WP fermentation | Optimal retention time for propionic production is 35 hours at 60°C            | • Reaction temperature and retention time considered in experiment design  
• Data revealed what type of results to expect from our experiment  
• Differences between reactor types |
| Totopotony WWWTP   | Simulate aerobic and anaerobic stages of Bio-P to determine cause of failure.         | • Failures caused by excessive retention times  
• At low pH levels, phosphorus accumulating organisms face greater competition from glycogen accumulating organisms and effluent phosphorus levels increase | • CWP looking to stabilize their Bio-P process  
• pH monitored in experiment |
5 Requirements

The CWP wants additional VFAs to achieve an 8:1 VFA: \( \text{PO}_4^{3-} \) mass ratio to stabilize their biological phosphorus removal process. The \( \text{PO}_4^{3-} \) concentration in the anaerobic zone with additional \( \text{PO}_4^{3-} \) from whey was calculated to be 6.18 mg/L, so a total VFA level of 30.8 mg/L is needed. At its lowest, VFA concentration is 24.9 mg/L in the anaerobic zone, a 6.6:1 ratio. To reach the desired 8:1 ratio, 5.9 mg/L VFAs must be produced from the whey. In terms of total mass, this equates to 468 kilograms of VFAs per day.

Due to an addition of 25,000 gallons/day from the whey and its fermentation byproducts into an anaerobic zone with a total flow of 22.8 MGD, the total weight rather than concentration of necessary additive VFAs was calculated. Daily addition of 468 kilograms of VFAs is needed to reach the 8:1 ratio.

<table>
<thead>
<tr>
<th>VFA:PO(_4^{3-}) ratio</th>
<th>7 to 1</th>
<th>8 to 1</th>
<th>10 to 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required anaerobic zone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VFA content</td>
<td>26.5 mg/L</td>
<td>30.3 mg/L</td>
<td>38.5 mg/L</td>
</tr>
<tr>
<td>Required VFA addition to meet ratio</td>
<td>2.1 mg/L</td>
<td>5.9 mg/L</td>
<td>13.6 mg/L</td>
</tr>
<tr>
<td>Required VFA to meet ratio</td>
<td>2283 kg</td>
<td>2611 kg</td>
<td>3318 kg</td>
</tr>
<tr>
<td>Required VFA addition to meet ratio</td>
<td>140 kg</td>
<td>468 kg</td>
<td>1175 kg</td>
</tr>
</tbody>
</table>

The fermentation process must take place at a convenient location within the CWP, to allow for easy injection of VFAs into the anaerobic zone. In addition, the CWP required transporting the weekly 175,000 gallons of whey from Country Fresh and storing it on site. Finally, the CWP required a method of integrating the fermenter into the existing system (Figure 10).
6 Design Criteria, Alternatives, and Decisions

6.1 Transportation

6.1.1 Needs
The whey must be transported five miles from Country Fresh to the CWP.

6.1.2 Alternatives
Trucking and pipeline methods were evaluated in terms of annual cost and complexity. Country Fresh already uses trucks to transport its whey to the hog farmers, simplifying the search for an effective trucking company. However, trucking requires the annual cost of gas and driver wages.

The pipeline method would entail designing and installing a one to four inch pipeline to deliver the whey underground from Country Fresh to the CWP, including a necessary pipeline crossing of major roads and highways. The cost of construction, permits, engineering design, and worker wages all factor into this alternative. Also, the complexity of obtaining permits, investigating different directional drilling companies to complete the pipeline, and looking up Miss Digs must be considered. After construction and installation, this alternative requires minimal annual maintenance costs.
6.1.3 Selection
Whey To React chose trucking methods to transport the whey from Country Fresh to the CWP. A decision matrix was unnecessary for this decision, as the evidence overwhelmingly pointed to trucking as the better approach. The pipeline option required lower annual maintenance costs than the trucking, but trucking has lower total costs and complexity.

6.2 Location of Whey Storage and Digestion

6.2.1 Needs
The location at the CWP must have enough room to hold the volume of whey produced by Country Fresh, space for a heat exchanger to heat the whey, access for delivery trucks, proximity to a biogas processor, and proximity to the anaerobic zone of secondary treatment.

6.2.2 Alternatives
Whey To React considered an unused aeration basin, the odor control building, and the underground pipe gallery with respect to the five criteria listed in the previous section.

The aeration basin (Figure 12) can hold 700,000 gallons, more than enough volume for the amount of whey Country Fresh produces. This basin’s proximity to the anaerobic zone allowed for lower piping material costs. The basin eliminated the need for buying a storage tank and digester to house the whey; however, this open-air basin would require a cover for proper fermentation.

Figure 9. Unused aeration basin considered for whey storage
The odor control building, or Building Z (Figure 13), provides easy access to the anaerobic zone and the biogas disposal system. A driveway leading up to the edge of the building offers easy truck access. Additionally, existing intake valves, which were meant for chemicals, could simplify unloading the whey from the trucks to a storage tank inside the building. Despite the convenience of this location, it can only store and ferment 50% of the whey. Furthermore, the distance between Building Z and the pipe gallery increases piping costs. Finally, the odor control building has no heating, so heating costs for the fermenter will increase during the winter.

Figure 10. The odor control building’s available space for storage and fermentation

The pipe gallery (Figure 14), located directly underneath and next to the anaerobic zone, requires a heated digester due to size constraints. This location requires the least heat, as the temperature averages 1 70°F. A driveway directly above the pipe gallery affords easy access to the location; however, the underground locale would complicate installation and mandate the construction of a containment wall around the storage and digester tanks.

---

1 Arithmetic average, not geometric average or log mean.
6.2.3 Selection

No decision matrix was needed for selection. Sealing off the basin to preclude oxygen is too complex; the odor control building, too small. Whey To React chose the pipe gallery.

6.3 Continuous Flow or Batch Process in Fermenter

A fermenter can operate in plug flow, continuous flow, or batch conditions. Whey To React immediately ruled out a plug flow reactor because it would yield a lower VFA concentration.

A continuous flow process would involve two separate tanks: one for storage and one for fermentation. The whey would be unloaded into the storage tank then pumped into a well-mixed fermenter at a rate of 17.4 GPM. 17.4 GPM of the VFA stream is pumped into the anaerobic zone in the CWP’s system. The volume in the fermenter would remain constant, due to the equal flow rates. The storage tank would allow for extra whey to be accumulated during the week and added to the anaerobic zone over the weekend while none is being delivered.

A batch process would also involve two tanks; however, both of these could ferment the whey. The truck would unload the whey to a different tank each day. Likewise, the tanks would alternate: receiving and fermenting one day, and pumping VFAs into the anaerobic zone the next day.

Whey To React chose a continuous flow design with a storage tank and fermenter for the CWP. The continuous flow design would provide the CWP with a more consistent flow of VFAs, since mixing
ensures proper fermentation. Continuous flow is also less expensive, requiring only one heat exchanger to the batch design’s two.

6.4 Storage Tank and Fermenter

6.4.1 Needs
Choosing the pipe gallery constrained the storage tank and fermenter design to 24 feet by 64 feet by 16 feet of useable space.

6.4.2 Selection
Based on literature findings, a 25,000 gallon fermenter heated to 99°F yields a one day retention time for VFA production (Table 5).

<table>
<thead>
<tr>
<th>Temperature (deg F)</th>
<th>Retention time (Hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>104</td>
<td>18</td>
</tr>
<tr>
<td>86</td>
<td>35</td>
</tr>
<tr>
<td>68</td>
<td>70</td>
</tr>
<tr>
<td>60</td>
<td>101</td>
</tr>
<tr>
<td>50</td>
<td>140</td>
</tr>
</tbody>
</table>

Whey To React chose a 30,000 gallon anaerobic reactor as a contingency. A cylindrical tank of this size, utilizing all 16 feet of vertical space, would have a diameter of 18 feet (Figure 16). This diameter allows enough clearance on both sides for maintenance, as well as space for a heat exchanger.

Whey To React selected a storage tank of the same volume and dimensions as the fermenter.

Figure 12. Rough overview of pipe gallery size constraints with selected storage tank and anaerobic digester
6.5 Heat Exchanger

6.5.1 Needs
The heat exchanger must heat the influent whey to the desired temperature while at the same time compensating for the conductive heat loss out the sides of the fermenter. The whey is assumed to enter the tank at 70° F and must be heated to 100°F. As illustrated in Table 6 below, this requires 271250 Btu/hour. For conductive heat loss, four different materials—concrete, stainless steel, fiber reinforced plastic (FRP), and aluminum—were considered for the analysis, assuming a wall thickness of one foot and ambient temperature of 70° F. A summary of the total heat loss is presented in Table 6.

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductive heat loss (Btu/hour)</th>
<th>Influent Whey Heating (Btu/Hour)</th>
<th>Total Heat Loss (Btu/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>14738</td>
<td>271250</td>
<td>285988</td>
</tr>
<tr>
<td>Steel</td>
<td>428754</td>
<td>271250</td>
<td>700004</td>
</tr>
<tr>
<td>FRP</td>
<td>4636</td>
<td>271250</td>
<td>275886</td>
</tr>
<tr>
<td>Aluminum</td>
<td>5493419</td>
<td>271250</td>
<td>5764669</td>
</tr>
</tbody>
</table>

6.5.2 Alternatives
Heating methods considered included steam injection, internal heat exchanger, and external heat exchanger. Steam injection heating consists of injecting steam into the whey stream as it travels from the storage tank to the anaerobic digester. According to Huchel et al., this is the most efficient option (2006); however, injecting steam into the whey would increase the flow volume entering the anaerobic digester and require a boiler, both of which increase space demands. An internal heat exchanger would be contained inside of the fermenter, saving space, but all literature highlighted the complexity of internal heat exchangers. An external heat exchanger would require additional space to draw the whey out of the digester at a specified flow rate, run it through a series of coils to heat the whey, and inject it back into the digester.

6.5.3 Selection
Space constraints warranted the rejection of the injection system. Based on literature reviews, an internal heat exchanger is too complex to install and maintain. Therefore, Whey To React selected an external heat exchanger.

6.6 Tank and Fermenter Features

6.6.1 Needs
The fermenter requires: a mixing method to ensure a well-mixed product, a pump to transport the whey to the anaerobic zone at 5 GM on average, and pipe connecting it to the anaerobic zone.
6.6.2 Alternatives
A recirculation pump is the only mixing method alternative. It withdraws whey from one area of the tank and injects it into another.

Whey To React considered two main alternatives for piping: ductile iron and PVC pipe. Ductile iron possesses greater strength, roughness, life span, and cost than PVC pipe.

As for the transport pumps, Whey To React considered a positive displacement pump and a centrifugal pump. Positive displacement pumps use pressure differentials to move fluid, while centrifugal pumps use the rotational kinetic energy from a motor to drive flow.

6.6.3 Evaluation
The only decision which required a design matrix was which material to use for piping. Whey To React liked the strength bonus associated with ductile iron, but wasn’t fond of the increased cost.

6.6.4 Selection
Whey To React chose a recirculation pump as the mixing method.

As shown in Table 7, Whey To React chose PVC pipe as the best option for piping material. Although ductile iron had a higher strength and a slightly higher life expectancy, PVC still met all the strength constraints, and was also recommended for use by the CWP.

<table>
<thead>
<tr>
<th>Piping Design Matrix</th>
<th>Wall Pressure</th>
<th>Roughness</th>
<th>Cost</th>
<th>Life Expectancy</th>
<th>Durability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Importance Factor</td>
<td>0.1</td>
<td>0.1</td>
<td>0.6</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>PVC</td>
<td>8</td>
<td>10</td>
<td>10</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>Ductile Iron</td>
<td>10</td>
<td>9</td>
<td>4</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

Centrifugal pumps handle better on both low flow rates and varying flows. Therefore, centrifugal pumps were chosen as the transport pump.

Design decisions are summarized in Figure 17.
Figure 13: Process Flow Diagram of System Components
7 Budget

The team’s budget for this project consists of gas money from driving back and forth to the CWP, about 25 minutes from Calvin College. All other needs have been either free or included in the cost of tuition.

The expected budget for the project construction includes the material costs of the storage tank, fermenter, piping, heat exchanger, trucking, and pumps; the cost of construction and integration into the existing system; and the annual costs of gas for the trucks and electricity for the heat exchanger and pumps (Table 8).

Table 8. Project budget

<table>
<thead>
<tr>
<th>Transportation</th>
<th>Item</th>
<th>Item Cost</th>
<th>Quantity</th>
<th>Upfront Costs</th>
<th>Costs per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck</td>
<td>$95,000.00</td>
<td>1</td>
<td>$95,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Transportation</td>
<td></td>
<td></td>
<td>$95,000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System</th>
<th>Item</th>
<th>Item Cost</th>
<th>Quantity</th>
<th>Upfront Costs</th>
<th>Costs per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage Tanks</td>
<td>$150,000.00</td>
<td>1</td>
<td>$150,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anaerobic Digester</td>
<td>$150,000.00</td>
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<td>$150,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PVC Piping</td>
<td>$0.79</td>
<td>400 ft.</td>
<td>$316</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pumps</td>
<td>$500.00</td>
<td>2</td>
<td>$1,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat Exchanger</td>
<td>$100,000.00</td>
<td>1</td>
<td>$100,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circulation Pump</td>
<td>$400.00</td>
<td>1</td>
<td>$400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total System</td>
<td>$401,716.00</td>
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<td></td>
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</table>

<table>
<thead>
<tr>
<th>Operation/Maintenance</th>
<th>Item</th>
<th>Item Cost</th>
<th>Quantity</th>
<th>Upfront Costs</th>
<th>Costs per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>$0.08</td>
<td></td>
<td></td>
<td></td>
<td>$17,520</td>
</tr>
<tr>
<td>Gas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$17,625</td>
</tr>
<tr>
<td>Driver</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$37,333</td>
</tr>
<tr>
<td>Maintenance</td>
<td>$15/hour</td>
<td>96 hours</td>
<td></td>
<td></td>
<td>$2,000</td>
</tr>
<tr>
<td>Total System</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$74,478</td>
</tr>
</tbody>
</table>

Total  $496,316.00 $74,478.00
Total with 25% Contingency  $713,492.50
8 Pilot Testing

8.1 Introduction

Whey To React intended on running a whey fermentation experiment to simulate the fermentation that would occur inside of the reactor they design; however, a whey sample was received too late in the semester to conduct the experiment. Instead it will be completed in Calvin College’s Interim period during January 2013. In the meantime the whey is being stored in the Biology lab Cold Storage at 4° C. According to Rao et al., “Samples stored at 4°C did not exhibit significant increases in levels of lactic acid or galactose” (2004). The whey stored in these conditions will not begin fermenting or create more lactic acid; it is stable.

From this experiment, Whey To React will identify the amount of VFAs produced and the optimal retention time. Calculations on VFA production, retention time, temperature of reaction and accompanying heat loss were all calculated based on the 2006 experiment by Morales et al. After the official experiment is performed by Whey To React next January, all calculations will be updated. The experiment standard operating procedure is outline below.

8.2 Materials and Methods

Necessary materials include:

- 1000 mL flask
- whey
- three one-way plastic valves
- a custom-made fermenter cap (Morales et al., 2006)
- tubing
- multiple test tubes
- a stir plate
- a magnetic stir bar
- a pH probe
- a dissolved oxygen sensor
- a nitrogen source, pipets
- an Ion Chromatography (IC) machine
- buffer solutions (4,7,10)
- Pasteur pipets

The experiment will be performed in the Chemical Engineering Lab, and the VFA analysis will be performed using the IC machine provided by the Chemistry Department.

8.2.1 Experimental Design

Experiment Standard Operating Procedure is outlined in Figure 24.
**Procedure:**

2. Add 600 mL of whey byproduct to 1000 mL flask with stir bar on stir plate.
3. Use pipet to take three 3 mL samples of whey – test for pH level and VFA content.
4. Create airtight seal using fermentor cap and one way plastic valves.
5. Flush headspace with nitrogen.
7. Use pipet to take three 3 mL samples of whey after four hours – transfer to test tube.
8. Test sample for pH level, then test for VFAs using IC machine experiment obtained from Dionex.
9. Record data.
10. Repeat every four hours until pH level drops rapidly or VFA content plateaus – expect 35 or so hours.

*Figure 14. Experimental procedure for January’s whey fermentation experiment*

Experiment apparatus set up is shown in Figure 19.

*Figure 15: Experiment Apparatus (Morales et al., 231)*
8.2.2 Data and Analytical Methods

Since Whey To React’s whey fermentation experiment has yet to be performed, there has been no data recorded from said experiment. As previously stated, all calculations requiring VFA content, retention time, or temperature concerns were performed using data from the 2006 experiment by Morales et al; however, after the whey fermentation is performed, a pH probe will be used to determine the pH value of the fermented whey, and an IC machine will be used to determine the VFA concentration.

8.3 Results

As shown in Figure 20, the propionic acid concentration peaks at around 35 hours with a concentration of around 3 g/L, while the acetic acid remains constant at around 1.8 g/L. This yields a total peak VFA concentration of around 4.8 g/L at a retention time of 35 hours when the fermentation occurs at 86 °C.

![Figure 16. Acetic and propionic acid concentration vs. retention time (Morales et al, 232)](image)

8.4 Discussion

Using the results from the 2006 experiment by Morales et al, it was calculated that 454 kilograms of VFAs per day could be added to the CWP’s phosphorous removal system. This would raise the VFA:PO₄³⁻ mass ratio at the point of lowest VFA concentration from its current 6.6:1 up to 7.9:1, just underneath the optimal 8:1 ratio.

Although these results provided a basis for feasibility calculations, they are not entirely reliable. The model experiment added bacteria prior to fermentation while Whey To React will not. This will simulate the actual fermenter, where no bacteria will be added prior to the whey. Calculations will be updated as data from the experiment becomes available.
8.5 Implications (for Design)

Key to design is peak VFA production, which takes place at a retention time of 35 hours at 30 °C; however, for every 10 °C the temperature drops, the retention time required to yield the same VFA concentration doubles. A larger retention time would result in a larger digester, which limits location choice. A shorter retention time would require heating or insulation, which increases cost.

9 Basis of Design

Fermenting whey is an efficient way to obtain the additional VFA’s the CWP desires for phosphorous removal. The addition of a storage tanks and fermenter in the pipe gallery of the CWP was found to be the most feasible solution.

The whey byproduct created at Country Fresh shall be stored in an existing tank. From this tank, the whey shall be loaded onto trucks using equipment already in place and driven the five miles to the CWP’s driveway overhead of the pipe gallery (Figure 21). The whey shall be transported every day of the week, in volumes of 25,000 GPD.

Figure 17. The driveway above the pipe gallery. The secondary treatment stage can be seen on the far right.

The whey shall then be unloaded from the truck into the 30,000 gallon storage tank. From the storage tank, the whey shall be pumped into the 30,000 gallon fermenter at a rate of around 17.4 GPM, where it shall be heated to 99°F by an external heat exchanger and mixed by a recirculation pump. A
centrifugal pump shall pump the fermented whey into the anaerobic zone of the secondary treatment stage at 17.4 GPM. Successful biological phosphorus removal should occur. The biogas produced from the fermentation shall be piped to the odor control building, where it shall be scrubbed, as is the standard protocol at the CWP.

10 Acknowledgements

Whey To React would like to thank Country Fresh Dairy for its help regarding whey and its properties. We’d also like to thank the City of Wyoming Clean Water Plant for all of its help and information regarding their Clean Water Plant, with special thanks to Myron Erickson, Aaron Vis, and John Burke, who were very quick to respond to our e-mails requesting guidance and data. We’d also like to thank Professor David Wunder, who met with us weekly to point us in the right direction and offer us advice on topics we were not familiar with.

We’d also like to thank James Flamming and David Filipiak of Fishbek, Thompson, Carr & Huber, Inc. for their taking the time to sit down with us and discuss the project, and give their advice on where to go next from that point in our project. The pizza they provided at that meeting was also cause for thanks. In addition, we’d like to thank Lori Keen of the Biology Department for providing storage space for our whey samples, Scott Prentice from the Chemistry and Biochemistry Department for help using the Ion Chromatography machine (IC), and Dr. Chad Tatko from the Chemistry and Biochemistry Department for help with analytical methods. Thanks to Art Schlicht of Walker Process Equipment for the heat exchanger quote and to Rich Huisman in the chemistry department for helping us order chemicals for the experiment. We’d finally like to specifically thank Jon Niebor for his help in creating our team’s website.
11 References


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Appendix A. CWP Effluent Permit

PERMIT NO. M10024392

PART I

Section A. Limitations and Monitoring Requirements

1. Final Effluent Limitations, Monitoring Point 001A

During the period beginning on the effective date of this permit and lasting until the expiration date of this permit, the permittee is authorized to discharge treated municipal wastewater from Monitoring Point 001A through Outfall 001. Outfall 001 discharges to the Grand River. Such discharge shall be limited and monitored by the permittee as specified below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Maximum Limits for Quantity or Loading</th>
<th>Maximum Limits for Quality or Concentration</th>
<th>Monitoring Frequency</th>
<th>Sample Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Monthly 7-Day Daily Units</td>
<td>Monthly 7-Day Daily Units</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow</td>
<td>(report) -- (report) MGD</td>
<td>-- -- --</td>
<td>Daily</td>
<td>Report Total Daily Flow</td>
</tr>
<tr>
<td>Carbonaceous Biochemical Oxygen Demand (CBOD₅)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>June 1 – Sept. 30</td>
<td>2600 5300 -- lbs/day</td>
<td>15 18 mg/l</td>
<td>Daily</td>
<td>24-Hr Composite</td>
</tr>
<tr>
<td>Oct. 1 – May 31</td>
<td>4600 7300 -- lbs/day</td>
<td>25 40 mg/l</td>
<td>Daily</td>
<td>24-Hr Composite</td>
</tr>
<tr>
<td>Total Suspended Solids</td>
<td>6500 8300 -- lbs/day</td>
<td>30 45 mg/l</td>
<td>Daily</td>
<td>24-Hr Composite</td>
</tr>
<tr>
<td>Ammonia Nitrogen (as N)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>June 1 – Sept. 30</td>
<td>1500 -- lbs/day</td>
<td>-- 8.0 mg/l</td>
<td>Daily</td>
<td>24-Hr Composite</td>
</tr>
<tr>
<td>Oct. 1 – May 31</td>
<td>-- -- lbs/day</td>
<td>-- (report) mg/l</td>
<td>Daily</td>
<td>24-Hr Composite</td>
</tr>
<tr>
<td>Total Phosphorus (as P)</td>
<td>150 -- lbs/day</td>
<td>1.0 mg/l</td>
<td>Daily</td>
<td>24-Hr Composite</td>
</tr>
<tr>
<td>Fecal Coliform Bacteria</td>
<td>-- --</td>
<td>200 400 ct/100 ml</td>
<td>Daily</td>
<td>Grab</td>
</tr>
<tr>
<td>Total Residual Chlorine</td>
<td>--</td>
<td>-- 0.038 mg/l</td>
<td>Daily</td>
<td>Grab</td>
</tr>
<tr>
<td>Total Mercury</td>
<td>(report) -- lbs/day</td>
<td>(report) -- mg/l</td>
<td>Quarterly</td>
<td>Grab</td>
</tr>
</tbody>
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12-Month Rolling Average

<table>
<thead>
<tr>
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<th>12-Month Rolling Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Mercury</td>
<td>0.00073 lbs/day</td>
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<tr>
<td></td>
<td></td>
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</tbody>
</table>

Minimum Monthly

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimum Monthly</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBOD₅, Minimum % Removal</td>
<td>Oct. 1 – May 31 85 % Monthly Calculation</td>
</tr>
<tr>
<td>Total Suspended Solids Minimum % Removal</td>
<td></td>
</tr>
</tbody>
</table>

Minimum Daily Maximum Daily

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimum Daily Maximum Daily</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>6.5 S.U. Daily Grab</td>
</tr>
<tr>
<td>Dissolved Oxygen</td>
<td></td>
</tr>
<tr>
<td>June 1 – Sept. 30</td>
<td>5.0 mg/l Daily Grab</td>
</tr>
<tr>
<td>Oct. 1 – May 31</td>
<td>3.0 mg/l Daily Grab</td>
</tr>
</tbody>
</table>
# Appendix B: First Semester Work Schedule

|---------|-------------------------------------------------------------------------------------------------|------|------|
| Sept. 17-23 | *Define project  
*Preliminary meeting with Prof. Wunder  
*Set up meeting infrastructure  
*Define team name | Oct. 29-Nov. 4 | *Write out rough fermentation experiment  
*Revised VFA production calculations  
*Update mass balance with new information  
*Update schematic  
*Continue researching experiments and case studies |
| Sept. 24-30 | *Research phosphorus removal techniques  
*Read through last year’s Clean Water Plant project  
*Tour of Clean Water Plant  
*Meet with library research man  
*Preliminary budget formation | Nov. 5-11 | *Second tour of Clean Water Plant  
*Begin draft PPFS  
*Finish VFA calculations  
*Update mass balance with new information  
*Begin research on reactors  
*Cost estimate |
| Oct. 1-7 | *Heavy initial research on Bio-P and whey fermentation  
*Begin writing list of questions for CWP staff  
*Form idea of fermentation experiment  
*Research to understand WWTPs | Nov. 12-18 | *Finish draft PPFS  
*Finish project poster  
*Meeting with Industrial Consultant  
*E-mail third large list of questions/data requests to CWP  
*Research on reactors/where to store at CWP |
| Oct. 8-14 | *Continued research on Bio-P and whey fermentation  
*E-mail CWP large list of questions, concerns, and request for data  
*Create initial grocery list for fermentation experiment  
*Begin wading through initial data from CWP  
*Research so that data from CWP could be understood | Nov. 19-25 | *Consider overall feasibility  
*VFA calculations using statistical data  
*Research on reactors  
*Research on implementation  
*Research on whey from discharge to introduction into CWP |
| Oct. 15-21 | *Write project brief for industrial consultant  
*Work on project presentation  
*Continue to decipher data and information from CWP  
*Run statistics on data from CWP  
*Work on PPFS outline  
*Continue Bio-P and whey fermentation research  
*Research more experiments and case studies | Nov. 26-Dec. 2 | *Final fermentation experiment write-up  
*Research IC machine experiments  
*Tour of Country Fresh – understand whey creation  
*Final VFA calculations  
*Rewrite PPFS  
*Heat loss calculations  
*Research on reactors and piping  
*Begin final design decision-making process |
| Oct. 22-28 | *Finish up web-site creation  
*Complete PPFS outline  
*Continue researching experiments and case studies  
*Draw up schematic of removal at CWP  
*Initial VFA production calculations  
*E-mail second huge list of question/concerns to CWP  
*Begin mass balance with available information | Dec. 3-9 | |