Pacific Gas and Electric Company

Emerging Technologies Program

Application Assessment Report No. 0612

Wine Stabilization through Electrodialysis

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1. EXECUTIVE SUMMARY

1.1. Objective of Study

Assess the electrical energy and demand savings that could result from using an Electrodialysis System in place of cold stabilization of wine.

1.2. Major Conclusions

Implementing electrodialysis wine stabilization instead of traditional cold stabilization (without enhancement) may result in significant electrical energy savings. Another non-energy related advantage of electrodialysis technology is an increase in stabilization rate, reducing the stabilization time of traditional cold stabilization of typically weeks to a few days.

However, this study shows that electrodialysis technology results in an increase in water consumption as well as the resulting wastewater which would need to be treated. Table 1-1 compares the performance of cold stabilization with electrodialysis stabilization.

<table>
<thead>
<tr>
<th>TABLE 1-1 COLD VS ELECTRODIALYSIS WINE STABILIZATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stabilization Method</td>
</tr>
<tr>
<td>Energy Consumption</td>
</tr>
<tr>
<td>Average Demand</td>
</tr>
<tr>
<td>Increase in Water Consumption</td>
</tr>
<tr>
<td>Adjusted Energy Consumption*</td>
</tr>
<tr>
<td>Stabilization Period</td>
</tr>
<tr>
<td>Initial Conductivity Drop</td>
</tr>
<tr>
<td>Final Conductivity Drop</td>
</tr>
<tr>
<td>Volume of Stabilized Wine</td>
</tr>
<tr>
<td>Energy Intensity</td>
</tr>
</tbody>
</table>

* The adjusted cold stabilization energy consumption considers the added tank and bare pipe insulation. The adjusted electrodialysis stabilization energy consumption considers the extra energy needed for wastewater treatment. The energy consumption for the increased electrodialysis water consumption is based on the Secondary Wastewater Treatment (activated sludge system) Baseline Study.

Table 1-2 summarizes the type of wine that was tested in this study as well as some background information regarding the tanks that the wine was cold stabilized in.
### TABLE 1-2 INFORMATION REGARDING WINE AND TANKS IN STUDY

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tank 952</th>
<th>Tank 953</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wine Variety Tested</td>
<td>2006 Pinot Grigio</td>
<td>2006 Pinot Grigio</td>
</tr>
<tr>
<td>Initial Volume of Wine</td>
<td>9,250 gallons</td>
<td>8,813 gallons</td>
</tr>
<tr>
<td>Type of Tank</td>
<td>Uninsulated, jacketed stainless steel tank</td>
<td>Uninsulated, jacketed stainless steel tank</td>
</tr>
<tr>
<td>Tank Capacity</td>
<td>9,250 gallons</td>
<td>9,250 gallons</td>
</tr>
<tr>
<td>Tank Location</td>
<td>Indoor</td>
<td>Indoor</td>
</tr>
</tbody>
</table>

#### 1.3. Key Findings

After analyzing the collected data it was determined that:

1. Electrodialysis Stabilization may result in significant electrical energy savings (approximately 99% savings)
2. Electrodialysis Stabilization may result in significant demand savings (approximately 79% reduction in demand)
3. A significant portion of the energy used in Cold Stabilization may be due to the chemistry of crystallization and the resulting interactions between the ions and complexing factors.
2. PROJECT BACKGROUND

2.1. Wine Stabilization

Wine stabilization as part of the winemaking process reduces the concentration of potassium bitartrate (cream of tartar) in wine. Traditionally, wineries lower the potassium bitartrate solubility in wine by chilling the wine to approximately 27 ºF. Wines are typically maintained at this temperature for a period of 1.5 to 3 weeks, depending on how easy it is to crystallize the potassium bitartrate, i.e. how “stable” the wine is. Several factors can influence the crystallization rate of potassium bitartrate, among them:\footnote{Refrigeration for Winemakers, Ray White, Ben Adamson, Bryce Rankine, Winetitles, Winemaking Series, 1998}

- Nucleation: the number of nuclei on which crystals can form and grow.
- Diffusion: the rate at which the dissolved potassium bitartrate comes into contact with the crystal formations.
- The rate at which crystals grow.
- Grape variety.

Once the desired potassium bitartrate concentration is achieved, the wine is filtered and pumped to holding tanks, ready to be bottled.

2.2. Technologies for Cold Stabilization Enhancement

There are different kinds of cold stabilization enhancement that may expedite the process\footnote{Refrigeration for Winemakers, Ray White, Ben Adamson, Bryce Rankine, Winetitles, Winemaking Series, 1998}. One variation of this process is the Contact Process, where the chilled wine is seeded with potassium bitartrate and mixed into the wine. Mixing in the potassium bitartrate seeds hastens the crystallization rate in the wine. The crystals left behind after wine filtration can be ground and reused to seed the next batch.

Another variation of cold stabilization is the Filtration Process, where wine is filtered through a potassium bitartrate bed. As wine flows through the bed, the potassium bitartrate in the wine crystallizes in the filter bed. Wine may be passed through the crystal bed several times, until wine is stabilized.

A third variation of cold stabilization is the Crystal Flow Process. This process involves chilling the wine to temperatures between 14 ºF and 21 ºF (freezing point of wine). Freezing the wine will generate potassium bitartrate and ice crystals. These crystals act as nuclei for further crystal growth. This process requires using scraped-surface heat exchangers.
2.3. Metric for Cold Stabilization

There are various methods used to determine wine stability with respect to potassium bitartrate crystallization and they vary depending on the winemaker. Some of these methods include:

- Chill proofing followed by a Concentration Product (CP) Test
- Chill proofing followed by visual inspection
- Filtering at 25 °F for 24 hours followed by visual inspection
- Wine freeze/slush test
- Conductivity test

The stability test used in this study is the Conductivity Test and is described below.

Conductivity Test: The conductivity test is performed by taking a wine sample from the stabilization tank. Throughout the test, the wine sample is maintained at the lowest temperature that the wine is expected to encounter. The sample wine is mixed and its conductivity is recorded. The sample is then seeded with potassium bitartrate (KHT) and mixed. Wine conductivity is measured and logged (approximately every 1 to 2 minutes) for a period of approximately 30 minutes. If the final conductivity value varies by less than 5% compared to the initial conductivity value, the wine is determined to be stable. Typically, stable dry white wines will have conductivities between 1,400 and 1,600 micro-Siemens per centimeter ($\mu$S/cm)$^2$.

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*A Review of Potassium Bitartrate Stabilization of Wines*, Bruce Zoecklein, Department of Horticulture, Virginia Polytechnic Institute and State University, 1998
2.4. Application of Electrodialysis for Wine Stabilization

Electrodialysis (ED) process, used for wine stabilization, removes the tartaric acids from the wine by passing it through an electric field and collecting ions (potassium ($K^+$), calcium ($Ca^{++}$) and negatively charged tartaric acids) on anionic and cationic membranes.

![Simplified Schematic of Ion Extraction on the Electrodialysis Process](image)

$TA^- = \text{Negatively charged tartaric acid.}$

**Figure 2-1** Simplified Schematic of Ion Extraction on the Electrodialysis Process

Inside the ED system there are two chambers separated by a cationic membrane. The first chamber holds the wine; the second chamber contains a solution of potassium and calcium ions that have been extracted by applying an electric field across the wine. Water flows through the second chamber creating a brine solution made up of the potassium and calcium ions. Jean-Louis Escudier (2002) shows a simplified schematic of ion migration within a single cell, which is reproduced in Figure 2-1. Figure 2-1 shows that the potassium and calcium ions migrate from Compartment #1 to Compartment #2 within its own cell, however the Tartaric Acid migrates from Compartment #1 to Compartment #2 of an adjacent cell. Each cell has an electric potential drop of approximately 1 Volt.
3. FIELD EVALUATION OF ENERGY CONSUMPTION OF ELECTRODIALYSIS AND COLD STABILIZATION

3.1. Overall Measurement Plan

This study compares the electrical energy consumption of traditional wine stabilization (cold stabilization) to that of electrodialysis wine stabilization. Wine from the same batch (2006 Pinot Grigio) was processed through cold stabilization and electrodialysis stabilization. Each system processed approximately 20,000 gallons of wine. Electrical energy consumption, temperatures, timing of equipment, wine tank levels, water consumption, flow rates and wine conductivity were monitored and logged for the duration of the study (from January through April 2007). A detailed description of measurement points for each system is described in the Instrumentation and Measurement Systems in Section 3.3. To accurately compare the electrical energy consumption of both systems, it was determined when wine conductivity reached 2.5%, the wine would be considered stable and data logging would be stopped.

As a baseline, the project considers a dedicated chiller system supplying chilled glycol to cool two 9,250 gallon tanks (cold stabilization). Glycol is chilled through a 40 hp water cooled reciprocating compressor and pumped to the stabilization tanks. The chiller compressor and condenser are located outdoors in a pad beside the Barrel Room. The two 9,250 gallon uninsulated stabilization tanks are located inside the Barrel Room which is maintained at approximately 50º F. The baseline used for the study considers cold stabilization in its most basic form, with no mixing, seeding or any stabilization “enhancement.” A simplified schematic of the cold stabilization system is shown in Figure 3-1 on the following page. The specifications for the refrigeration system used for cold stabilization are shown in Table 3-1.

The tested electrodialysis system is a portable system mounted into a trailer (model STARS ED-600 by Winesecrets). The trailer was “plugged” to an electrical outlet inside one of the tank rooms. Wine is pumped from the fermentation tanks to the ED trailer and processed through as many loops as necessary to reach the desired wine conductivity. Once the target conductivity is reached, wine is pumped to a holding tank, ready for bottling. In addition to the wine recirculation pump used in the ED system, water pumps are used to move the brine solution and wash the membranes once a batch is done. The ED system requires three water lines: a hard water line, a hot water line and a soft water line. A simplified schematic of the ED system is shown in Figure 3-2 on the following page.

<table>
<thead>
<tr>
<th>Table 3-1 Cold Stabilization Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Equipment</strong></td>
</tr>
<tr>
<td>Refrigeration Compressor</td>
</tr>
<tr>
<td>Glycol Pump</td>
</tr>
<tr>
<td>Cooling Tower</td>
</tr>
<tr>
<td>Condenser Water Pump</td>
</tr>
</tbody>
</table>
Figure 3-1  Simplified Schematic of the Cold Stabilization System

Figure 3-2  Simplified Schematic of the Electrodialysis System
3.2. Description of the Site

The study was hosted by a winery located in Northern California. As stated earlier, the uninsulated tanks used for cold stabilization were located inside the Barrel Room. Figure 3-3 below shows the iced tanks. The blue “colored” ice is due to a minor glycol leak from the refrigeration system.

![Figure 3-3 Uninsulated Cold Stabilization Tanks](image)

The chiller, compressor and cooling tower were located on a pad outside the Barrel Room. Figure 3-4 shows the cooling tower as well as the 40 hp reciprocating refrigeration compressor. To the left of the refrigeration compressor is the glycol return tank and behind it (not shown) the glycol supply pump. Ice buildup can be seen on the uninsulated pipe section coming right out of the refrigeration compressor, before pipe insulation begins.
Finally, the portable electrodialysis system (inside the trailer) is shown in Figure 3-5. On the right side is one of the temperature sensors and data loggers used to record the wine temperature as it comes into the electrodialysis machine. The three cylindrical shapes at the center are pumps used to circulate the wine within the electrodialysis machine, and pumps used to circulate water. On the far back (behind the blue hoses) are the electrodialysis membranes where the electric field is applied. On the other side of the machine (behind the pumps) are two wine holding tanks. Finally, tied around the middle pump, is a motor On/Off data logger.
Figure 3-5  Electrodialysis System
3.3. **Instrumentation and Measurement Systems**

The following equipment was used to log the parameters needed for the present analysis:

- **Electrical Energy Consumption and Power:**
  - DENT ElitePro Logger with current transducer
  - AEMC Instruments Model 3910

- **Temperature:**
  - PACE XR440 Pocket Logger with thermistor sensor
  - HOBO H08-032-08 Pro RH/TEMP

- **Equipment On/Off Status:**
  - DENT TOUM MagLogger
  - HOBO U12-008 Industrial data logger with current transducer

- **Flow Meter:**
  - Controlotron 1010WDP1 with clamp-on ultrasonic sensor

In addition, the winery personnel helped record, throughout the duration of the study, the following data:

- Wine temperature in the cold stabilization tanks
- Cold stabilization tank level
- Cold stabilization wine conductivity
- Cold stabilization wine pH
- Water consumption of the ED system
- Starting and Finishing conductivity for electrodialysis stabilized wine.

Tables 3-2 and 3-3 identify the measurement points for the Electrodialysis and Cold Stabilization systems, respectively.

<table>
<thead>
<tr>
<th>Measured Parameter</th>
<th>Logging Method</th>
<th>Logging Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wine Inlet Temperature</td>
<td>Data Logger</td>
<td>15 min.</td>
</tr>
<tr>
<td>Wine Outlet Temperature</td>
<td>Data Logger</td>
<td>15 min.</td>
</tr>
<tr>
<td>Wine Initial Conductivity</td>
<td>Winery Personnel</td>
<td></td>
</tr>
<tr>
<td>Wine Final Conductivity</td>
<td>Winery Personnel</td>
<td>End</td>
</tr>
<tr>
<td>Wine Initial pH</td>
<td>Winery Personnel</td>
<td>Start</td>
</tr>
<tr>
<td>Wine Final pH</td>
<td>Winery Personnel</td>
<td>End</td>
</tr>
<tr>
<td>Electrical Energy Consumption of ED System</td>
<td>Data Logger</td>
<td>15 min.</td>
</tr>
<tr>
<td>Water Consumption</td>
<td>Winery Personnel</td>
<td>1/batch</td>
</tr>
<tr>
<td>ED Pump On/Off Status</td>
<td>Data Logger</td>
<td>Varies</td>
</tr>
<tr>
<td>Measured Parameter</td>
<td>Logging Method</td>
<td>Logging Interval</td>
</tr>
<tr>
<td>---------------------------------------------------------</td>
<td>------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>Outdoor Air Temperature</td>
<td>Data Logger</td>
<td>15 min.</td>
</tr>
<tr>
<td>Barrel Room Ambient Temperature</td>
<td>Data Logger</td>
<td>15 min.</td>
</tr>
<tr>
<td>Stabilization Tank Surface Temperature (T952)</td>
<td>Data Logger</td>
<td>15 min.</td>
</tr>
<tr>
<td>Stabilization Tank Surface Temperature (T953)</td>
<td>Data Logger</td>
<td>15 min.</td>
</tr>
<tr>
<td>Stabilization Tank Well Temperature (T952)</td>
<td>Data Logger</td>
<td>15 min.</td>
</tr>
<tr>
<td>Stabilization Tank Well Temperature (T953)</td>
<td>Data Logger</td>
<td>15 min.</td>
</tr>
<tr>
<td>Wine Temperature (T952)</td>
<td>Winery Personnel</td>
<td>2/day</td>
</tr>
<tr>
<td>Wine Temperature (T953)</td>
<td>Winery Personnel</td>
<td>2/day</td>
</tr>
<tr>
<td>Stabilization Tank Level (T952)</td>
<td>Winery Personnel</td>
<td>2/day</td>
</tr>
<tr>
<td>Stabilization Tank Level (T953)</td>
<td>Winery Personnel</td>
<td>2/day</td>
</tr>
<tr>
<td>Wine Conductivity (T952)</td>
<td>Winery Personnel</td>
<td>Varies</td>
</tr>
<tr>
<td>Wine Conductivity (T953)</td>
<td>Winery Personnel</td>
<td>Varies</td>
</tr>
<tr>
<td>Wine pH (T952)</td>
<td>Winery Personnel</td>
<td>Varies</td>
</tr>
<tr>
<td>Wine pH (T953)</td>
<td>Winery Personnel</td>
<td>Varies</td>
</tr>
<tr>
<td>Glycol Flow Rate (at by-pass pipe)</td>
<td>Spot Measurement</td>
<td>Once</td>
</tr>
<tr>
<td>Glycol Supply Temperature</td>
<td>Data Logger</td>
<td>15 min.</td>
</tr>
<tr>
<td>Glycol Return Temperature</td>
<td>Data Logger</td>
<td>15 min.</td>
</tr>
<tr>
<td>Cooling Tower Fan Motor Current</td>
<td>Data Logger</td>
<td>15 min.</td>
</tr>
<tr>
<td>Cooling Tower Fan On/Off Status</td>
<td>Data Logger</td>
<td>15 min.</td>
</tr>
<tr>
<td>Glycol Supply Pump Power</td>
<td>Spot Measurement</td>
<td>Once</td>
</tr>
<tr>
<td>Condenser Pump Power</td>
<td>Spot Measurement</td>
<td>Once</td>
</tr>
<tr>
<td>Chiller Compressor Power (idle)</td>
<td>Spot Measurement</td>
<td>Once</td>
</tr>
<tr>
<td>Electrical Energy Consumption of Chiller System</td>
<td>Data Logger</td>
<td>15 min.</td>
</tr>
</tbody>
</table>

T952 = Stabilization Tank 952 and T953 = Stabilization Tank 953.
4. RESULTS

4.1. Cold Stabilization Measurements and Analysis

Cold Stabilization Timeline

Figure 4-1 helps illustrate the cold stabilization progression throughout the study.

![Figure 4-1 Stabilization Tank 953 Well Temperature](image)

Cold stabilization had two major setbacks, where the refrigeration system had to be shutdown for repairs. Figure 4-1 shows the temperature inside one of the stabilization tanks used in the study. The timeline for cold stabilization can be described as follows:

- Measurement instrumentation is installed on January 8, 2007.
- Tanks are sterilized (hot water) on January 16, 2007.
- Wine is immediately pumped to the tanks after sterilization. Wine temperature is very close to the Barrel Room ambient temperature (about 47 °F).
- The refrigeration system comes online on January 24, 2007.
- The first refrigeration system breakdown occurs on January 29, 2007, thus wine temperature starts rising.
- The refrigeration system is repaired on February 2, 2007, and wine temperature stabilizes on February 5, 2007.
- The second breakdown happened on February 13, 2007. The irregular temperature spike shown between February 14 and 15, 2007 is due to the well temperature sensor coming loose, thus temperature readings are an average between the wine temperature and the...
Barrel Room ambient temperature. The refrigeration system came back online on February 19, 2007.

- The last wine conductivity reading was taken on March 28, 2007 although the wine was kept chilled until April 3, 2007 and pumped out of the stabilization tanks.

**Cold Stabilization Period**

Although the wine took 63 days to stabilize (from January 24, 2007 to March 28, 2007), the net stabilization period should be significantly shorter due to the two major refrigeration system breakdowns. Figure 4-2 illustrates wine conductivity for one of the stabilization tanks. The two increases in conductivity (from January 29 through February 2 and February 13 through February 19) shown in Figure 4-2 reflect the refrigeration system breakdowns. There is an additional conductivity increase starting on March 14. This may be due to the slight temperature fluctuation shown in Figure 4-1. Unfortunately, the winery personnel were not able to identify the cause for the temperature fluctuation.

![Figure 4-2 Wine Conductivity for Tank 953](image)

In order to account for the extra energy it took to bring down the conductivity to its original value before the refrigeration system breakdowns, the extra time (and energy) for the periods of 1/29/07 (1:00 p.m.) through 2/5/07 (11:00 a.m.) and 2/16/07 (8:00 a.m.) through 2/23/07 (8:00 a.m.) have been discarded. Therefore the net cold stabilization period is 46 days (1,108 hours).

Please note that temperature fluctuations during the stabilization process may have adverse effects on the crystallization rate\(^4\). However, this effect has not been considered in our analysis.

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\(^4\) *A Review of Potassium Bitartrate Stabilization of Wines*, Bruce Zoecklein, Department of Horticulture, Virginia Polytechnic Institute and State University, 1998
The crystallization process happens in two phases: the induction phase (where precipitates appear in wine due to solubility change caused by chill proofing) and the crystal growth phase. The drastic “slope” change in Figure 4-2 delimits these two phases. Also, Figure 4-2 shows that cold stabilization reduced wine conductivity variation in Tank 953 from 15.5% down to 3.2%.

Cold Stabilization Energy Analysis

Wine temperature was brought down from approximately 50 °F to 28 °F. During the 46 days required to stabilize the wine in Tanks 952 and 953, the refrigeration system (which includes the refrigeration compressor, glycol supply pump, cooling tower fan and cooling tower pump) consumed approximately 26,891 kWh. Figure 4-3 shows the electrical demand for the whole refrigeration system.

![Figure 4-3 Refrigeration System Demand](image)

The average demand while dropping the wine temperature from 50 °F to 28 °F was 25.2 kW. The average demand required to maintain the tank temperature at 28 °F was approximately 24.2 kW.

Based on a thermodynamic model of the cold stabilization system, the total electrical energy consumption can be broken down into the following components:\(^5\):

- **Cooling wine from 50 °F to 28 °F (both tanks)**
  - Cooling the wine = 297 kWh
  - Heat gain from tank sides and top = 538 kWh
  - Heat gain from ground = 21 kWh
  - Formulation of ice on tank surface = 873 kWh

\(^5\) Calculation details for the thermodynamic model of the cold stabilization system can be found at the end of the report in the Appendix Section.
Heat gain due to uninsulated pipes = 25 kWh

Maintaining Tank Temperature at 28 ºF (both tanks)
Heat gain form tank sides and top = 6,920 kWh
Heat gain from ground = 89 kWh
Heat gain due to uninsulated pipes = 372 kWh

Total electrical energy consumption = 9,135 kWh

Comparing the thermodynamic model electrical energy consumption with measured data shows that only 42% of the electrical energy has been accounted for in the model. It is suspected that the remaining balance is due to energy required by the wine chemistry.

4.2. Electrodialysis Measurements and Analysis

Electrodialysis Stabilization and Energy Analysis

Electrodialysis stabilization lasted approximately 1.5 days, from January 23, 2007 (9:40 a.m.) through January 24, 2007 (4:11 p.m.). During this period, 21,500 gallons of wine were stabilized by reducing the conductivity change from 14.6% to 2.5%. Figure 4-4 shows the electrodialysis system demand (which includes pumps and membrane electric field generator). The total electrical energy consumption for the electrodialysis system was approximately 165 kWh.

![Electrodialysis System Demand](image-url)

Figure 4-4  Electrodialysis System Demand
The average electrical demand for the electrodialysis system is approximately 5 kW. Based on specifications from the electrodialysis manufacturer, the equipment can process wine for approximately 12 hours before it requires CIP (clean-in-place), which typically lasts 1.5 hours. The cleaning cycles are clearly identified in Figure 4-4.

**Electrodialysis Water Consumption**

The electrodialysis system requires hard, soft and hot water to operate. Water is mostly used to move the brine solution after dialysis takes place and to perform CIP (clean-in-place) after each 12 hour cycle, or at the end of the batch.

The winery personnel recorded the water consumption used by the electrodialysis system for the period of December 18, 2006 through February 15, 2007. For the batch considered in this study, the total water consumption was 6,664 gallons, which is approximately 31% of the total wine volume processed. However, the water consumption for this particular batch was unusually high. To more accurately analyze the water consumption of the electrodialysis system, we will consider the total water consumption processed from December 18, 2006 through February 15, 2007. The total water consumption was approximately 69,948 gallons which represents approximately 14% (504,611 gallons) of the total volume of wine processed through the electrodialysis system for the same period.

When considering the economics of an electrodialysis system versus traditional cold stabilization it is important to note that the winery will consume more water (equivalent to 14% of the amount of wine processed through the electrodialysis system). Additionally, if the winery has no waste water ponds, then the wastewater will need to be treated, thus it is necessary to consider the extra energy used for wastewater treatment.

### 4.3 Limitations on Energy and Demand Savings

The baseline considered in this study does not include stabilization tank insulation or stabilization enhancements like wine seeding, mixing, etc. However, to more accurately portray the common practices used in Northern California Wineries, we have adjusted the electrical energy consumption of the cold stabilization system by considering tank insulation on the tank sides.

Additionally, recognizing that the new electrodialysis system will result in added water usage and wastewater due to the process, we have included the extra energy that will be required to process the wastewater before discharging it out of the facility.

### 4.4 Summary of Energy and Demand Savings

There may be significant electrical energy and demand savings for stabilizing wine with an electrodialysis system as opposed to traditional cold stabilization. Table 4-1 compares the electrodialysis wine stabilization performance to wine cold stabilization.
From Table 4-1, electrodialysis stabilization would result in an overall system energy intensity of 7.9 Wh/gal and cold stabilization would result in an overall system energy intensity of 1,200 Wh/gal. It is expected that electrodialysis stabilization could save approximately 99% of the energy used by traditional cold stabilization.

<table>
<thead>
<tr>
<th>Stabilization Method</th>
<th>Cold Stabilization</th>
<th>Electrodialysis Stabilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Consumption</td>
<td>26,891 kWh</td>
<td>165 kWh</td>
</tr>
<tr>
<td>Average Demand</td>
<td>24 kW</td>
<td>5 kW</td>
</tr>
<tr>
<td>Increase in Water Consumption</td>
<td>0 gallons</td>
<td>3,010 gallons</td>
</tr>
<tr>
<td>Adjusted Energy Consumption*</td>
<td>22,965 kWh</td>
<td>170 kWh</td>
</tr>
<tr>
<td>Stabilization Period</td>
<td>1,108 hours</td>
<td>31 hours</td>
</tr>
<tr>
<td>Initial Conductivity Drop</td>
<td>14.8%</td>
<td>14.6%</td>
</tr>
<tr>
<td>Final Conductivity Drop</td>
<td>3.4%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Volume of Stabilized Wine</td>
<td>18,500 gallons</td>
<td>21,500 gallons</td>
</tr>
<tr>
<td>Energy Intensity</td>
<td>1,200 Wh/gal</td>
<td>7.9 Wh/gal</td>
</tr>
</tbody>
</table>

* The adjusted cold stabilization energy consumption considers the added tank and bare pipe insulation. The adjusted electrodialysis stabilization energy consumption considers the extra energy needed for wastewater treatment.
5. CONCLUSIONS

Application of Electrodialysis Stabilization Technology

Based on a brief discussion with the winery personnel, the winery was extremely satisfied with the performance of the electrodialysis system. The facility did not notice any adverse effect on the quality of wine produced. Additionally, the winery was very happy with the reduction in stabilization time that was observed when compared to traditional cold stabilization.

Besides the increased water consumption and potential wastewater treatment that may be necessary, the electrodialysis stabilization technology may be considered as a suitable alternative to cold stabilization.

Energy and Demand Savings due to Application of Electrodialysis Technology

Using electrodialysis wine stabilization as opposed to traditional cold stabilization, in the absence of any enhancements, may result in significant electrical energy and demand savings. Based on the study performed, for a small system that cold stabilizes approximately 20,000 gallons of wine, it is expected that application of electrodialysis stabilization could result in approximately 23,842 kWh savings when compared to cold stabilization and reduce the average electrical demand by 19 kW.

These results may vary depending on the type of wine, chilling system and the cold stabilization method.

Other Associated Issues

Because only 42% of the electrical energy consumption of the refrigeration system was accounted for in the thermal model, a full energy balance of the system would require a more detailed analysis of the wine chemistry for the crystallization process.

It is important to note that electrodialysis may increase water consumption at the facility (by approximately 14% of the total volume of wine that is processed trough electrodialysis) resulting in additional wastewater. The added wastewater will need to be treated, which may increase the initial capital cost of an electrodialysis system (to include the wastewater treatment equipment).
6. APPENDIX

6.1. Thermodynamic Model for Cold Stabilization

The thermodynamic analysis for cold stabilization includes the following:

- Estimate of electrical energy required for initially cooling the wine to the desired (steady state) temperature.
- Estimate of electrical energy required by the refrigeration system to compensate for the heat gain to the wine tank (from the sides, top and bottom of tank) from warmer ambient conditions.
- Estimate of electrical energy required to form the layer of ice (which acts as a layer of insulation) on the tank wall surface, since the tank is not insulated.
- Estimate of electrical energy required by refrigeration system to compensate for the heat gain to the uninsulated portions of the glycol supply and bypass pipelines.
- Estimate the cooling load provided by the glycol based on measured data.

Section 6.3 shows the equations that were used in our thermodynamic analysis of the system and Section 6.4 shows a sample of the calculations performed for Tank 952. A summary of the thermodynamic analysis yields the results presented in Table 6-1 below.

<table>
<thead>
<tr>
<th>TABLE 6-1 RESULTS OF THERMODYNAMIC ANALYSES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Initial Cooling of Wine to Desired Temperature</strong></td>
</tr>
<tr>
<td>Energy Required to Cool Wine to Desired Temperature</td>
</tr>
<tr>
<td>Energy Required to Compensate for Heat Gain to Tank Sides and Top of Tank</td>
</tr>
<tr>
<td>Energy Required to Compensate for Heat Gain from Bottom of Tank</td>
</tr>
<tr>
<td>Energy Required to Form Ice on Tank Surface</td>
</tr>
<tr>
<td>Energy Required to Compensate for Heat Gain to Uninsulated Glycol Pipelines</td>
</tr>
<tr>
<td><strong>Total Energy Required During Initial Cooling of Wine</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Steady State Cooling (Holding Wine at Desired Temperature)</strong></th>
<th><strong>Tank 952 (kWh)</strong></th>
<th><strong>Tank 953 (kWh)</strong></th>
<th><strong>Both Tanks (kWh)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Required to Compensate for Heat Gain to Tank Sides and Top of Tank</td>
<td>3,516</td>
<td>3,404</td>
<td>6,920</td>
</tr>
<tr>
<td>Energy Required to Compensate for Heat Gain from Bottom of Tank</td>
<td>44</td>
<td>45</td>
<td>89</td>
</tr>
<tr>
<td>Energy Required to Compensate for Heat Gain to Uninsulated Glycol Pipelines</td>
<td>372</td>
<td>372</td>
<td>372</td>
</tr>
<tr>
<td><strong>Total Energy Required During Steady State Cooling of Wine</strong></td>
<td><strong>7,381 kWh</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| **Total Energy Required to Compensate for Heat Gain During Cold Stabilization** | **9,135 kWh** |
From Table 6-1, it can be seen that the total energy required by the refrigeration system during the cold stabilization process is estimated to be 9,135 kWh based on our thermodynamic model. This compares to the measured energy consumption of 26,891 kWh from logged data.

A separate analysis of the cooling load provided by the glycol was performed for comparison with the two above methods. Based on measured data for the following parameters:

- Glycol supply temperature
- Glycol tank temperature
- Glycol bypass flowrate
- Nominal glycol pump flow (from pump nameplate data)

the electrical energy required by the refrigeration system to provide the necessary glycol cooling was calculated to be 24,322 kWh.

A comparison of the 3 sets of data shows that the glycol cooling analysis compares fairly closely with the logged data, with a difference of less than 8%. However, there is a huge discrepancy between the thermodynamic analyses of the heat gain to the wine tank in comparison with the other two values. This can be contributed, but not limited, to the following issues:

- Energy required for crystallization
- Glycol leak, which happened towards the end of cold stabilization.

6.2. Project Timeline and Key Dates

Originally the project was scheduled to last two months; the first month allocated to collect data and the second month for analysis and reporting. However, the refrigeration system used for cold stabilization had two major shutdowns due to failure of cooling tower basin level sensor and a minor glycol leak. Due to these two events, cold stabilization did not end until the end of April 2007. Table 6-2 outlines the project timeline and identifies key dates throughout the study.

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Kickoff Meeting</td>
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<tr>
<td>Monitoring Planning</td>
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<tr>
<td>ED Monitoring</td>
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<tr>
<td>Cold Stab. Monit.</td>
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<tr>
<td>Data Analysis</td>
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<tr>
<td>Report Development</td>
<td></td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>

![Color-coded Timeline]

- Refrigeration System Failure
- First Draft Due
- Report Due Date

Electrodialysis Wine Stabilization
6.3. Equations Used for Thermodynamic Model Analysis

This section presents the equations that were used in our thermodynamic model to estimate the energy required by the facility’s refrigeration system to compensate for the various sources of heat losses.

**Volume of Tank**

The volume of wine in a tank can be calculated as follows:

\[
V = \left(\pi D_{\text{Tank}}^2/4\right) \times (H_{\text{Tank}} - x)
\]

Where,

- \(D_{\text{Tank}}\) = diameter of tank, feet
- \(H_{\text{Tank}}\) = height of tank, feet
- \(x\) = distance from top of tank to the level of wine, feet

The surface area of the sides of the tank that is covered in ice is estimated as:

\[
A_{\text{side}} = \left(\pi D_{\text{Tank}}\right) \times (H_{\text{Tank}} - x)
\]

Since the tank is not completely filled with wine, the heat transfer from the sides of the tank (up to the wine level) will be different than the heat transfer from the top of the tank. It should also be noted that 50% of the tank is jacketed for glycol circulation (see Figure 3-3) and the rest of the tank is not jacketed.
Equations for Analysis of Energy Used for Cold Stabilization

**a - Amount of Energy to Cool Wine to Desired Temperature**
The amount of electrical energy required to cool a given volume of wine, $E_{R_{Cooling}}$, can be estimated as follows:

\[
E_{R_{Cooling}} = V \times \rho \times C_p \times (T_{initial} - T_{final}) / (COP \times C_4)
\]

Where,

- $V$ = volume of wine being cooled, gallons
- $\rho$ = density of wine, lbm/gallon
- $C_p$ = specific heat of wine, Btu/lbm-°F
- $T_{initial}$ = initial temperature of wine, °F
- $T_{final}$ = final (or desired) temperature of wine, °F
- $C_4$ = Conversion factor, 3,412.2 Btu/kW-hr
- $COP$ = coefficient of performance of refrigeration system

**b - Energy Required for Tank to Come to Stabilization Temperature (Initial Cooling)**
*(Taken at Average Point Before Wine Has Reached Steady State Temperature)*

(i) **Convective Heat Transfer Coefficient** (ASHRAE Fundamentals Eq. 24-6)
The convective heat transfer coefficient, $h_{cv,i}$, is calculated as

\[
h_{cv,i} = C \times (1/d)^{0.2} \times (1/T_{avg,i})^{0.181} \times (T_{amb,i} - T_{s,i})^{0.266} \times [1 + 1.277(v_{wind})]^{0.5}
\]

where,

- $C$ = constant depending on shape and heat flow condition,
  (1.235 for longer vertical cylinders; 0.89 for horizontal plates, cooler than air facing upward)
- $d$ = for flat surfaces and large cylinders, $d = 24$ inches
- $T_{avg,i}$ = average temperature ($T_{avg} = (T_{amb} + T_{s}) / 2$), °F
- $T_{amb,i}$ = average ambient air temperature during initial cooling period (from measured data), °F
- $T_{s,i}$ = average tank surface temperature during initial cooling (prior to achieving steady state temperature), °F
- $v_{wind}$ = average air speed, mph

---

6 Detailed formulation of the heat transfer coefficient had also been compared to formulations from the following references and the results were very comparable:

(ii) Radiative Heat Transfer Coefficient (ASHRAE Fundamentals Eq. 24-7)
The radiation heat transfer coefficient, \( h_{\text{rad},i} \), is calculated as:

\[
h_{\text{rad},i} = \left[ \varepsilon \times \sigma \times (T_{\text{amb},i}^4 - T_{\text{s},i}^4) \right] / (T_{\text{amb},i} - T_{\text{s},i})
\]

where,

\[
\begin{align*}
\varepsilon &= \text{surface emittance} \\
\sigma &= \text{Stefan-Boltzmann constant, } 0.1713 \times 10^{-8} \text{ Btu/hr-ft}^2\text{-R}^4
\end{align*}
\]

The total heat transfer coefficient, \( h_i \), is the sum of the convective and radiative heat transfer coefficients:

\[
h_i = h_{\text{cv},i} + h_{\text{rad},i}
\]

(iii) Heat Gain to Tank Surfaces

Tank Sides
The heat gain (energy) rate, \( HG_{\text{side},i} \), from the sides of the tank surface during the initial cooling period can be estimated as follows:

\[
HG_{\text{side},i} = \frac{T_{\text{amb},i} - T_{\text{wine},i}}{h_{i,\text{side}} A_{\text{tank}}} + \frac{\Delta x_{\text{tank}}}{k_{\text{tank}} A_{\text{tank}}}
\]

Where,

\[
\begin{align*}
T_{\text{amb},i} &= \text{average ambient air temperature during initial cooling period (from measured data), } ^\circ\text{F} \\
T_{\text{wine},i} &= \text{average wine temperature during initial cooling (prior to achieving steady state temperature), } ^\circ\text{F} \\
h_{i,\text{side}} &= \text{the sum of the convective heat and radiation heat transfer coefficients for tank sides}^7, \text{ Btu/hr-ft}^2\text{-}\circ\text{F} \\
A_{\text{tank}} &= \text{area of sides of tank, ft}^2 \\
\Delta x_{\text{tank}} &= \text{thickness of tank wall, feet} \\
k_{\text{tank}} &= \text{thermal conductivity of tank wall material, Btu/hr-ft-}\circ\text{F}
\end{align*}
\]

---

\(^7\) Calculated from equations (6) and (7) on pages 24.16 and 24.17, Chapter 24 of ASHRAE 1997 Fundamentals
Top of Tank
The heat gain (energy) rate, \( HG_{\text{top},i} \), from the top of the tank during the initial cooling period can be estimated as follows:

\[
HG_{\text{top},i} = \frac{T_{\text{amb},i} - T_{\text{wine},i}}{\frac{1}{h_{i,\text{top}} A_{\text{top}}} + \frac{\Delta x_{\text{air},i}}{k_{\text{air}} A_{\text{top}}} + \frac{\Delta x_{\text{tan} k}}{k_{\text{tan} k} A_{\text{tan} k}}}
\]

Where,
- \( h_{i,\text{top}} \) = the sum of the convective heat and radiation heat transfer coefficients for top of tank,
- \( A_{\text{top}} \) = area of top of tank, \( \text{ft}^2 \)
- \( \Delta x_{\text{air},i} \) = thickness of layer of air between top surface of wine and tank during initial cooling period, feet
- \( k_{\text{air}} \) = thermal conductivity of air, Btu/hr-ft-°F

The term \( \frac{\Delta x_{\text{tan} k}}{k_{\text{tan} k} A_{\text{tan} k}} \) was calculated and was insignificant compared with the other two terms and have thus not been included in the sample calculations shown in Section 6.3.

(iv) Energy to Compensate for Heat Gain to Tank Sides and Top of Tank (Initial Cooling)
The amount of electrical energy (kWh) required to compensate for the heat gain from the sides of the tank during the initial cooling period, \( ER_{\text{side},i} \), can be estimated as follows:

\[
ER_{\text{side},i} = \frac{(HG_{\text{side},i} + HG_{\text{top},i}) \times H_i}{(\text{COP} \times C_4)}
\]

Where,
- \( HG_{\text{side},i} \) = heat gain rate to the tank from tank sides prior to wine achieving steady state temperature, Btu/hr
- \( H_i \) = hours that tank of wine is initially cooled prior to reaching steady state temperature, hr
- \( \text{COP} \) = coefficient of performance of refrigeration system (calculated based on measured data)
- \( C_4 \) = conversion constant, 3,412.2 Btu/kW-hr
(v) Energy to Compensate for Heat Gain from Ground (Initial Cooling)
The amount of electrical energy (kWh) required to compensate for the heat gain from the bottom of the tank due to the ground during the initial cooling period, ER_{ground,i}, can be estimated using the following relation extracted from Holman (1990)

\[
ER_{ground,i} = 2 \times k_g \times A_{top} \times (T_g - T_{wine,i}) \times \left[ H_i / (\pi \times \alpha) \right]^{0.5} / (COP \times C_4)
\]

Where,

- \(k_{air}\) = thermal conductivity of ground, Btu/hr-ft-°F
- \(A_{top}\) = area of top of tank, ft²
- \(T_g\) = average ground temperature, °F
- \(T_{wine,i}\) = average wine temperature during initial cooling (prior to achieving steady state temperature), °F
- \(H_i\) = hours that tank of wine is initially cooled prior to reaching steady state temperature, hr
- \(\alpha\) = thermal diffusivity of ground, ft²/s

c – Energy to Form Ice on the Tank Surface
The amount of electrical energy required for the formation of ice on the tank surface (ER_{sub}) can be estimated as:

\[
ER_{sub} = V_{ice} \times \rho_{ice} \times h_{sub} / (COP \times C_4)
\]

Where,

- \(V_{ice}\) = volume of ice on the tank surface (calculated based on surface area of tank sides and thickness of ice build-up on tank surface), ft³
- \(\rho_{ice}\) = density of ice, 57.25 lbm/ft³
- \(h_{sub}\) = latent heat of sublimation for ice, Btu/lbm

d & e – Energy to Compensate for Tank Heat Gain (Steady State Cooling)

(i) Convective Heat Transfer Coefficient (ASHRAE Fundamentals Eq. 24-6)
The convective heat transfer coefficient, \(h_{cv,ss}\), is calculated as

\[
h_{cv,ss} = C \times (1/d)^{0.2} \times (1/T_{avg,ss})^{0.181} \times (T_{amb,ss} - T_{ss})^{0.266} \times [1 + 1.277(v_{wind})]^{0.5}
\]

where,

- \(C\) = constant depending on shape and heat flow condition, (1.235 for longer vertical cylinders; 0.89 for horizontal plates, cooler than air facing upward)
- \(d\) = for flat surfaces and large cylinders, \(d = 24\) inches

---

(ii) Radiative Heat Transfer Coefficient (ASHRAE Fundamentals Eq. 24-7)
The radiation heat transfer coefficient, \( h_{\text{rad,ss}} \), is calculated as:

\[
h_{\text{rad,ss}} = \frac{\varepsilon \times \sigma \times (T_{\text{amb,i}}^4 - T_{\text{s,i}}^4)}{(T_{\text{amb,ss}} - T_{\text{s,ss}})}
\]

where,

\[
\varepsilon = \text{surface emittance}
\]
\[
\sigma = \text{Stefan-Boltzmann constant, } 0.1713 \times 10^{-8} \text{ Btu/hr-ft}^2\text{-R}^4
\]

The total heat transfer coefficient, \( h_i \), is the sum of the convective and radiative heat transfer coefficients:

\[
h_{\text{ss}} = h_{\text{cv,ss}} + h_{\text{rad,ss}}
\]

(iii) Heat Gain from Tank Surfaces

Tank Sides
The heat gain (energy) rate, \( H_{G_{\text{side,ss}}} \), from the sides of the tank surface during the steady state (holding) period can be estimated as follows:

\[
H_{G_{\text{side,ss}}} = \frac{T_{\text{amb,ss}} - T_{\text{wine,ss}}}{h_{\text{ss,side}} A_{\text{side}} + \frac{\Delta x_{\text{tank}}}{k_{\text{tank}}} + \frac{\Delta x_{\text{ice}}}{k_{\text{ice}}} A_{\text{side}}}
\]

Where,

\[
T_{\text{amb,i}} = \text{average ambient air temperature during steady state cooling period, } ^\circ\text{F}
\]
\[
T_{\text{wine,i}} = \text{average wine temperature during steady state cooling, } ^\circ\text{F}
\]
\[
h_{\text{ss,side}} = \text{the sum of the convective heat and radiation heat transfer coefficients for tank sides}^9, \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}
\]
\[
A_{\text{side}} = \text{area of sides of tank, ft}^2
\]
\[
\Delta x_{\text{tank}} = \text{thickness of tank wall, feet}
\]
\[
k_{\text{tank}} = \text{thermal conductivity of tank wall material, Btu/hr-ft}^-{\circ\text{F}}
\]
\[
\Delta x_{\text{ice}} = \text{thickness of ice build-up on tank wall, feet}
\]
\[
k_{\text{ice}} = \text{thermal conductivity of ice, Btu/hr-ft}^-{\circ\text{F}}
\]

---

9 Calculated from equations (6) and (7) on pages 24.16 and 24.17, Chapter 24 of ASHRAE 1997 Fundamentals
Top of Tank
The heat gain (energy) rate, \( \text{HG}_{\text{top,ss}} \), from the top of the tank during the steady state (holding) period can be estimated as follows:

\[
\text{HG}_{\text{top,ss}} = \frac{T_{\text{amb,ss}} - T_{\text{wine,ss}}}{\frac{1}{\bar{h}_{\text{ss, top}} A_{\text{top}}} + \frac{\Delta x_{\text{air, ss}}}{k_{\text{air}} A_{\text{top}}} + \frac{\Delta x_{\text{tank}}}{k_{\text{tank}} A_{\text{side}}}}
\]

Where,
- \( \bar{h}_{\text{ss, top}} \) = the sum of the convective heat and radiation heat transfer coefficients for top of tank,
- \( A_{\text{top}} \) = area of top of tank, ft\(^2\)
- \( \Delta x_{\text{air, ss}} \) = thickness of layer of air between top surface of wine and tank during steady state cooling period, feet
- \( k_{\text{air}} \) = thermal conductivity of air, Btu/hr-ft-\(^\circ\)F

The term \( \left( \frac{\Delta x_{\text{tank}}}{k_{\text{tank}} A_{\text{tank}}} \right) \) was calculated and found to be insignificant compared with the other two terms and have thus not been included in the sample calculations shown in Section 6.3.

(iv) Energy to Compensate for Heat Gain from Tank Sides and Top of Tank
(Steady State Cooling)

The amount of electrical energy (kWh) required to compensate for the heat gain from the sides of the tank during the steady state cooling period, \( \text{ER}_{\text{side,ss}} \), can be estimated as follows:

\[
\text{ER}_{\text{side,ss}} = \frac{(\text{HG}_{\text{side,ss}} + \text{HG}_{\text{top,ss}}) \times H_{\text{ss}}}{(\text{COP} \times C_4)}
\]

Where,
- \( \text{HG}_{\text{side,ss}} \) = heat gain rate to the tank from tank sides during steady state period, Btu/hr
- \( H_{\text{ss}} \) = hours that tank of wine is held at steady state temperature, hr
- \( \text{COP} \) = coefficient of performance of refrigeration system (calculated based on measured data)
- \( C_4 \) = conversion constant, 3,412.2 Btu/kW-hr
**f – Energy to Compensate for Heat Gain from Ground (Steady State Cooling)**

The amount of electrical energy (kWh) required to compensate for the heat gain from the bottom of the tank due to the ground during the steady state period, $ER_{\text{ground,ss}}$, can be estimated as follows:

$$ER_{\text{ground,ss}} = 2 \times k_g \times A_{\text{top}} \times (T_g - T_{\text{wine,ss}}) \times \left[H_{ss} / (\pi \times \alpha)\right]^{0.5} / (\text{COP} \times C_4)$$

Where,

- $k_g$ = thermal conductivity of ground, Btu/hr-ft-°F
- $A_{\text{top}}$ = area of top of tank, ft$^2$
- $T_g$ = average ground temperature, °F
- $T_{\text{wine,ss}}$ = average wine temperature during steady state cooling period, °F
- $H_{ss}$ = hours that tank of wine is held at steady state temperature, hr
- $\alpha$ = thermal diffusivity of ground, ft$^2$/s

**g – Energy to Compensate for Heat Gain Due to Uninsulated Glycol Piping**

**Convective Heat Transfer Coefficient** (ASHRAE Fundamentals Eq. 24-6)

The convective heat transfer coefficient, $h_{cv}$, is calculated as

$$h_{cv} = C \times (1/d)^{0.2} \times (1/T_{avg})^{0.181} \times (T_{\text{amb}} - T_s)^{0.266} \times [1 + 1.277(v_{\text{wind}})]^{0.5}$$

where,

- $C$ = constant depending on shape and heat flow condition,
  1.016 for horizontal cylinders;
  1.235 for longer vertical cylinders
- $d$ = diameter for cylinder, inches
- $T_{avg}$ = average temperature ($T_{avg} = (T_{\text{amb}} + T_s) / 2$), °F
- $T_{\text{amb}}$ = average ambient air temperature, °F
- $T_s$ = average surface temperature, °F
- $v_{\text{wind}}$ = average wind speed, mph

**Radiative Heat Transfer Coefficient** (ASHRAE Fundamentals Eq. 24-7)

The radiation heat transfer coefficient, $h_{\text{rad}}$, is calculated as:

$$h_{\text{rad}} = \left[\varepsilon \times \sigma \times (T_{\text{amb}}^4 - T_s^4)\right] / (T_{\text{amb}} - T_s)$$

where,

- $\varepsilon$ = surface emittance
- $\sigma$ = Stefan-Boltzmann constant, $0.1713 \times 10^{-8}$ Btu/hr-ft$^2$-R$^4$
The total heat transfer coefficient, $h_i$, is the sum of the convective and radiative heat transfer coefficients:

$$h_{pipe} = h_{cv} + h_{rad}$$

### Heat Gain from Uninsulated Glycol Pipelines

The heat gain by the uninsulated piping due to the outside ambient temperature, $HG_{pipe}$, can be estimated as follows:

$$HG_{pipe} = \frac{T_{amb} - T_{glycol}}{\frac{1}{h_{pipe} A_{pipe}} + \frac{\Delta x_{pipe}}{k_{pipe} A_{pipe}} + \frac{\Delta x_{ice}}{k_{ice} A_{pipe}}}$$

Where,

- $T_{amb}$ = average ambient air temperature, °F
- $T_{glycol}$ = average glycol temperature, °F
- $h_{pipe}$ = the sum of the convective heat and radiation heat transfer coefficients for uninsulated piping,
- $A_{pipe}$ = area of uninsulated piping, ft$^2$
- $\Delta x_{tank}$ = thickness of pipe wall, feet
- $k_{tank}$ = thermal conductivity of piping material, Btu/hr-ft-°F
- $\Delta x_{ice}$ = thickness of ice build-up on piping, feet
- $k_{ice}$ = thermal conductivity of ice, Btu/hr-ft-°F

### Energy to Compensate for Heat Gain by Uninsulated Glycol Piping

The amount of electrical energy (kWh) required to compensate for the heat gain from the uninsulated glycol pipelines, $ER_{pipe}$, can be estimated as follows:

$$ER_{pipe} = HG_{pipe} \times H_{cs} / (COP \times C_4)$$

Where,

- $HG_{pipe}$ = heat gain rate to the uninsulated glycol pipelines, Btu/hr
- $H_{cs}$ = total hours required for cold stabilization process, hr
- COP = coefficient of performance of refrigeration system (calculated based on measured data)
- $C_4$ = conversion constant, 3,412.2 Btu/kW-hr
### 6.4. Spreadsheet Snapshots of Thermodynamic Model Analysis

This section presents some snapshots taken from the Excel spreadsheet model for calculations of the refrigeration energy requirements.

#### Snapshot of Excel Spreadsheet for Initial Cooling Energy Requirements

<table>
<thead>
<tr>
<th>Tank</th>
<th>Volume of Wine</th>
<th>Density of Wine</th>
<th>Specific Heat of Wine</th>
<th>Initial Wine Temperature</th>
<th>Steady State Temperature</th>
<th>COP</th>
<th>Conversion Constant</th>
<th>Energy to Cool Wine</th>
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<tr>
<td>Task 912</td>
<td>0.533</td>
<td>8.15</td>
<td>1.13</td>
<td>47.44</td>
<td>20.7</td>
<td>1.84</td>
<td>3412.2</td>
<td>0.05</td>
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<td>0.1</td>
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<td>1.13</td>
<td>47.75</td>
<td>21.4</td>
<td>2.84</td>
<td>3412.2</td>
<td>0.05</td>
</tr>
</tbody>
</table>

#### (b) Heat Gain from Tank Surface (Before Ice Has Formed)

#### (c) Convective Heat Transfer Coefficient Calculations

<table>
<thead>
<tr>
<th>Tank</th>
<th>Shape Factor</th>
<th>Barred Room</th>
<th>Tank Surface</th>
<th>Average Air Temperature</th>
<th>Average Air Speed</th>
<th>Heat Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task 912 (Side-Fins-Jacketed)</td>
<td>1.235</td>
<td>24</td>
<td>51.75</td>
<td>33.89</td>
<td>42.7</td>
<td>0.199</td>
</tr>
<tr>
<td>Task 913 (Side-Fins-Jacketed)</td>
<td>1.235</td>
<td>24</td>
<td>51.75</td>
<td>33.89</td>
<td>42.7</td>
<td>0.199</td>
</tr>
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</table>

#### (d) Radiative Heat Transfer Coefficient Calculations

<table>
<thead>
<tr>
<th>Tank</th>
<th>Shape Factor</th>
<th>Barred Room</th>
<th>Tank Surface</th>
<th>Radiative Constant</th>
<th>Heat Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task 912 (Side-Fins-Jacketed)</td>
<td>0.6</td>
<td>1.71E-09</td>
<td>51.75</td>
<td>0.032</td>
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</tr>
<tr>
<td>Task 913 (Side-Fins-Jacketed)</td>
<td>0.6</td>
<td>1.71E-09</td>
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</table>

#### (e) Heat Gain from Tank Sidewall & Top of Tank

<table>
<thead>
<tr>
<th>Tank</th>
<th>Barred Room</th>
<th>Wine/Glycol</th>
<th>Tank Surface</th>
<th>Thickness of Tank Wall</th>
<th>Thermal Conductivity of Tank Wall</th>
<th>Thermal Conductivity of Ice</th>
<th>Air Thermal Conductivity</th>
<th>Heat Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task 912 (Side-Fins-Jacketed)</td>
<td>51.75</td>
<td>33.89</td>
<td>245.47</td>
<td>1.939</td>
<td>0.123</td>
<td>0.005</td>
<td>0.53</td>
<td>0.0410006</td>
</tr>
<tr>
<td>Task 913 (Side-Fins-Jacketed)</td>
<td>51.75</td>
<td>33.89</td>
<td>245.47</td>
<td>1.939</td>
<td>0.123</td>
<td>0.005</td>
<td>0.53</td>
<td>0.0410006</td>
</tr>
</tbody>
</table>
# Electrodialysis Wine Stabilization

## Snapshot of Excel Spreadsheet for Steady State Cooling Energy Requirements

<table>
<thead>
<tr>
<th>Tank</th>
<th>Shape (Front Flow)</th>
<th>Barrel Size</th>
<th>Tank Surface Temperature</th>
<th>Average Air Temperature</th>
<th>Average Air Speed</th>
<th>h_a</th>
<th>(Watt/(m²·K))</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>9</td>
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<tr>
<td>10</td>
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<tr>
<td>12</td>
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<td></td>
</tr>
</tbody>
</table>

**Energy Used to Compensate for Heat Gains from Tank Sides and Tank Top**

<table>
<thead>
<tr>
<th>Tank</th>
<th>Gain (kWh)</th>
<th>S.S. Cooling (kW)</th>
<th>COP</th>
<th>Constant (kWh</th>
<th>kW)</th>
<th>Energy Used (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>8</td>
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<tr>
<td>9</td>
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<tr>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Heat Gains from Tank Bottoms (When Wine Has Reached Steady State Temperature)**

- **Wine Tank Volume:** ~
- **Initial Cooling of Wine:** ~
- **Steady State - Tank Heat Gains:** ~
- **Uninsulated Piping Summary:** ~

---

**BASE**
### Electrolysis Wine Stabilization

#### Summary

**Page 33**

**Pacific Gas & Electric Company**

**Emerging Technologies Program**

**Snapshot of Excel Spreadsheet for Uninsulated Piping Energy Requirements**

### Table: Convection Heat Transfer Coefficients Calculations

<table>
<thead>
<tr>
<th>Tank</th>
<th>Shape Constant</th>
<th>Heat Flow Diameter</th>
<th>Length of Pipe</th>
<th>Ambient Temperature</th>
<th>Surface Temperature</th>
<th>Average Temperature</th>
<th>Average Air Speed</th>
<th>h_{ev} (Btu/hr-ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor Oxydr Supply Line (Initial)</td>
<td>1 016</td>
<td>2</td>
<td>50</td>
<td>51.75</td>
<td>22</td>
<td>22</td>
<td>2,703</td>
<td></td>
</tr>
<tr>
<td>Indoor Oxydr Supply Line (Steady State)</td>
<td>1 016</td>
<td>2</td>
<td>50</td>
<td>54.44</td>
<td>32</td>
<td>43.22</td>
<td>8</td>
<td>2,781</td>
</tr>
<tr>
<td>Outdoor Oxydr Expasse Line (Initial)</td>
<td>1 016</td>
<td>2</td>
<td>10</td>
<td>42.26</td>
<td>32</td>
<td>37.14</td>
<td>14</td>
<td>3,171</td>
</tr>
<tr>
<td>Outdoor Oxydr Expasse Line (Steady State)</td>
<td>1 016</td>
<td>2</td>
<td>10</td>
<td>54.44</td>
<td>32</td>
<td>43.22</td>
<td>8</td>
<td>3,750</td>
</tr>
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</table>

#### Table: Radiation Heat Transfer Coefficients Calculations

<table>
<thead>
<tr>
<th>Tank</th>
<th>Stefan-Boltzmann Constant</th>
<th>Ambient Temperature</th>
<th>Surface Temperature</th>
<th>h_{rt} (Btu/hr-ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor Oxydr Supply Line (Initial)</td>
<td>0.95</td>
<td>1.71</td>
<td>30</td>
<td>51.75</td>
</tr>
<tr>
<td>Indoor Oxydr Supply Line (Steady State)</td>
<td>0.95</td>
<td>1.71</td>
<td>30</td>
<td>54.44</td>
</tr>
<tr>
<td>Outdoor Oxydr Expasse Line (Initial)</td>
<td>0.95</td>
<td>1.71</td>
<td>30</td>
<td>42.26</td>
</tr>
<tr>
<td>Outdoor Oxydr Expasse Line (Steady State)</td>
<td>0.95</td>
<td>1.71</td>
<td>30</td>
<td>54.44</td>
</tr>
</tbody>
</table>

#### Table: Heat Gains from Tank Sizes & Top of Tank

<table>
<thead>
<tr>
<th>Tank</th>
<th>Ambient Temperature</th>
<th>Glycol Temperature</th>
<th>Tank Surface</th>
<th>h_{ev} (Btu/hr-ft²)</th>
<th>h_{rt} (Btu/hr-ft²)</th>
<th>Area (ft²)</th>
<th>Pipe Wall Conductivity (Btu/hr-ft²°C)</th>
<th>Thickness of Wall (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor Oxydr Supply Line (Initial)</td>
<td>51.75</td>
<td>30</td>
<td>25.18</td>
<td>2,703</td>
<td>0.823</td>
<td>0.94</td>
<td>0.53</td>
<td>0.04166667</td>
</tr>
<tr>
<td>Indoor Oxydr Supply Line (Steady State)</td>
<td>54.44</td>
<td>30</td>
<td>30</td>
<td>2,781</td>
<td>0.838</td>
<td>0.94</td>
<td>0.53</td>
<td>0.04166667</td>
</tr>
<tr>
<td>Outdoor Oxydr Expasse Line (Initial)</td>
<td>42.26</td>
<td>30</td>
<td>25</td>
<td>3,171</td>
<td>0.818</td>
<td>0.94</td>
<td>0.53</td>
<td>0.04166667</td>
</tr>
<tr>
<td>Outdoor Oxydr Expasse Line (Steady State)</td>
<td>54.44</td>
<td>30</td>
<td>25</td>
<td>3,750</td>
<td>0.823</td>
<td>0.94</td>
<td>0.53</td>
<td>0.04166667</td>
</tr>
</tbody>
</table>

#### Table: Energy Used to Compensate for Heat Gains from Tank Sizes & Tank Top

<table>
<thead>
<tr>
<th>Tank</th>
<th>Gain (Btu/hr)</th>
<th>Initial Cooling (°F)</th>
<th>COP</th>
<th>Conversion Constant</th>
<th>Energy Used (Btu/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor Oxydr Supply Line (Initial)</td>
<td>2,428</td>
<td>65</td>
<td>2.04</td>
<td>3412.2</td>
<td>32</td>
</tr>
<tr>
<td>Indoor Oxydr Supply Line (Steady State)</td>
<td>2,957</td>
<td>100</td>
<td>2.04</td>
<td>3412.2</td>
<td>309</td>
</tr>
<tr>
<td>Outdoor Oxydr Expasse Line (Initial)</td>
<td>313</td>
<td>80</td>
<td>2.04</td>
<td>3412.2</td>
<td>3</td>
</tr>
<tr>
<td>Outdoor Oxydr Expasse Line (Steady State)</td>
<td>313</td>
<td>80</td>
<td>2.04</td>
<td>3412.2</td>
<td>3</td>
</tr>
</tbody>
</table>
### Summary of Calculations

<table>
<thead>
<tr>
<th></th>
<th>Tank 952</th>
<th>Tank 953</th>
<th>Total for Both Tanks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial Cooling of Wine</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) Energy Required to Cool Wine to Desired Temperature</td>
<td>150</td>
<td>147</td>
<td>297</td>
</tr>
<tr>
<td>(b) Energy Required to Compensate Heat Gain to Tank Sides &amp; Top</td>
<td>273</td>
<td>264</td>
<td>537</td>
</tr>
<tr>
<td>(c) Energy Required to Compensate Heat Gain from Bottom of Tank</td>
<td>10</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>(d) Energy Required to Form Ice on Tank Surface</td>
<td>447</td>
<td>426</td>
<td>873</td>
</tr>
<tr>
<td>Energy Required to Compensate for Heat Gain to Glycol Supply Line</td>
<td></td>
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<td>22</td>
</tr>
<tr>
<td>Energy Required to Compensate for Heat Gain to Glycol Bypass Line</td>
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</tr>
<tr>
<td><strong>Total Energy Required</strong></td>
<td><strong>881</strong></td>
<td><strong>848</strong></td>
<td><strong>1,729</strong></td>
</tr>
<tr>
<td><strong>Steady State Cooling (Holding Wine at Desired Temperature)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(d) &amp; (e) Energy Required to Compensate Heat Gain to Tank Sides &amp; Top</td>
<td>3,516</td>
<td>3,404</td>
<td>6,920</td>
</tr>
<tr>
<td>(f) Energy Required to Compensate Heat Gain from Bottom of Tank</td>
<td>44</td>
<td>45</td>
<td>89</td>
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<tr>
<td>Energy Required to Compensate for Heat Gain to Glycol Supply Line</td>
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<td>109</td>
</tr>
<tr>
<td>Energy Required to Compensate for Heat Gain to Glycol Bypass Line</td>
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<td>61</td>
</tr>
<tr>
<td><strong>Total Energy Required</strong></td>
<td><strong>3,561</strong></td>
<td><strong>3,448</strong></td>
<td><strong>7,009</strong></td>
</tr>
<tr>
<td><strong>Total Energy Required to Compensate for Heat Losses During Cold Stabilization</strong></td>
<td></td>
<td></td>
<td><strong>9,135 kWh</strong></td>
</tr>
</tbody>
</table>
6.5. Graphs of Data Recorded During Cold Stabilization and Electrodialysis Tests

This section presents some graphs of the various measurements that were recorded throughout the cold stabilization and electrodialysis tests.

![Ambient Temperatures](image1)

**Figure 6.5-1 Ambient Temperatures**

![Cold Stabilization Tank Temperatures](image2)

**Figure 6.5-2 Cold Stabilization Tank Temperatures**
Figure 6.5-3 Electrodialysis Test Wine Temperature

Figure 6.5-4 Measured Electrical Demand for Cold Stabilization vs. Electrodialysis Tests
Figure 6.5-5 Measured Electrical Energy Consumption for Cold Stabilization vs. Electrodialysis Tests

Figure 6.5-6 Cold Stabilization Wine Conductivity Tests for Both Tanks