Comparative Analysis between Grundfos CRE 15-3 Variable Speed Centrifugal Pumps and a Worthington D-824 Constant Speed Centrifugal Pump in a KU Steam Power Plant Application

By

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Abstract

This document presents a comparative analysis between the use of a Grundfos CRE 15-3 variable speed centrifugal pump and a Worthington D-824 constant speed centrifugal pump in a steam power plant application. This was performed since, in many applications that require pumping systems, the pumps account for the majority of the energy expenses; and it is believed that, by using variable speed pumps in such applications, the pumps could help increase savings with regard to energy costs.

In the steam power plant located at The University of Kansas, these two pumps must supply water to a deaerator tank and to a heat exchanger, where the deaerator tank is the tank that provides water to the boilers inside the power plant. The heat exchanger is only used to capture the steam that is unused by the plant, turning such steam into water that can be reused to again supply water to the deaerator tank. The Grundfos CRE 15-3 has the ability to run in discharge pressure mode as well as level control mode, while the Worthington D-824 is only able to run in discharge pressure mode. With that in mind, data concerning the discharge pressure, flow rate and power consumption was collected when either the Grundfos CRE 15-3 variable speed pump or the Worthington D-824 supplied water to the system. A total of four different cases were considered when gathering this data: (1) Both pumps ran in discharge pressure mode while supplying water to the deaerator tank and the heat exchanger; (2) Both pumps ran in discharge pressure mode, but for part of the day they supplied water only to the deaerator tank, and, for the other part of the day, they supplied water to both the heat exchanger and the deaerator tank; (3) The Grundfos CRE 15-3 ran in level control mode only supplying water to the deaerator tank, while the Worthington D-824 ran in discharge pressure mode only supplying water to the deaerator tank; (4) The Grundfos CRE 15-3 ran in level control mode only supplying water to the deaerator tank, while the Worthington D-824 ran in discharge pressure mode supplying water to both the deaerator tank and the heat exchanger.

The gathered data was then compared to the theoretical pump data from their respective pump curves. A life cycle cost analysis was performed, using the BLLC5 software provided by the Department of Energy, to see if the variable speed pump would indeed provide energy savings to the power plant as well as have a lower total life cycle cost as compared to the constant speed pump. As this document will show, energy savings can be obtained when running the Grundfos

CRE 15-3 in level control mode, even though the total life cycle costs of both pumps are still fairly similar.

For Case 1 the Worthington D-824 pump had a total life cycle cost that was 3.14% lower than the CRE 15-3 pumps; and both pump systems have almost identical energy consumption. When the heat exchanger valve is open in Case 2, the Worthington D-824 pump's life cycle cost is 4.56% lower than the one that of the CRE 15-3 pumps. When the heat exchanger valve is closed, the total life cycle cost of both pump systems are almost identical (0.006% difference). For Case 3, the CRE 15-3 pumps' average energy costs are 68.8% lower than the costs of the Worthington D-824 pump. Even though there is a large difference in energy costs, the CRE 15-3 pumps' total life cycle cost is only 7.89% lower than the total life cycle cost of the Worthington D-824. Finally, a direct percentage comparison cannot be given for Case 4 due to the different jobs that the two pump systems were doing while operating. However, as will be shown in this document, reasonable estimates were made in an attempt to compare these pump systems for the scenario presented in Case 4.

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Nomenclature

A_0 = Series of equal cash amounts ($)

AC = Alternating Current (Amperes)

BHP = Break Horsepower (HP)

BLCC = Building Life Cycle Cost Software

C_d = Decommissioning/disposal costs (including restoration of the local environment and disposal of auxiliary services) ($)

C_e = Energy costs (predicted cost for system operation, including pump driver, controls, and any auxiliary services) ($)

C_{env} = Environmental costs (contamination from pumped liquid and auxiliary equipment) ($)

C_{ic} = Initial costs, purchase price (pump, system, pipe, auxiliary services) ($)

C_{in} = Installation and commissioning cost (including training) ($)

C_m = Maintenance and repair costs (routine and predicted repairs) ($)

C_o = Operation costs (labor cost of normal system supervision) ($)

C_s = Down time costs (loss of production) ($)

d = Discount rate (%)

DC = Direct current (Amperes)

DOE = U.S. Department of Energy

e = Constant escalation rate provide by DOE (%)

E = Present-value energy costs ($)

e_i = Error of a given instrument (%)

FEMP UPV* = Factor for use with energy costs (%)

FEMP = Federal Energy Management Program

ft = Fuel type (Only used in Life cycle cost analysis)

F_t = Future cash amount in PV formula for one time amounts ($)

H = Head in feet (ft)

H_p = Pressure supplied by the pump (Head of pressure)

H_s = Pressure required by the process (Head of pressure)

I = Present-value investment costs ($)

lb = Pound mass (lb)

LCC = Life Cycle Cost in present-value dollars of a given alternative ($)

LCCA = Life Cycle Cost Analysis

n = Number of years in the study period

N = Total number of errors being considered in Equation (3)

OM&R = Present-value non-fuel operating, maintenance, and repair costs ($)

P = Pressure (PSI)

∆P = Differential Pressure (PSI)

PV = Present Value ($)

Q = Flow rate (GPM)

reg = Region

Repl = Present-value capital replacement costs ($)

Res = Present-value of residual value (resale value, scrap value, salvage value) less disposal costs ($)

rt = Rate type

SG = Specific Gravity

SPV = Single Present Value Factor (%)

T = Time (In Figures) (Days, Hours, Minutes)

t = Year

u_I = Total instrumentation error (%)

UPV = Uniform Present Value Factor (%)

UPV* = Uniform Present Value modified for price escalation (%)

$\dot{W}$ = Power (kW)

$\dot{W}$**(HP)** = Pump hydraulic power (HP)

W = Present-value of water costs ($)

η = Pump efficiency (%)

Chapter 1: Introduction and Scope of Work

1.1 Constant Speed Pumps

In the world today, pumping systems account for almost 20% of the world's electrical energy demand as well as 25% to 50% of the energy being used in certain municipal applications [1]. Also, many of these systems are operating at rates much lower than optimal efficiency, which gives plenty of room for energy savings [1]. According to Budris [2], in industrial plants, depending upon the motor size and the percentage of operating time, pumps can have energy costs ranging from US$10,000 up to US$100,000 annually.

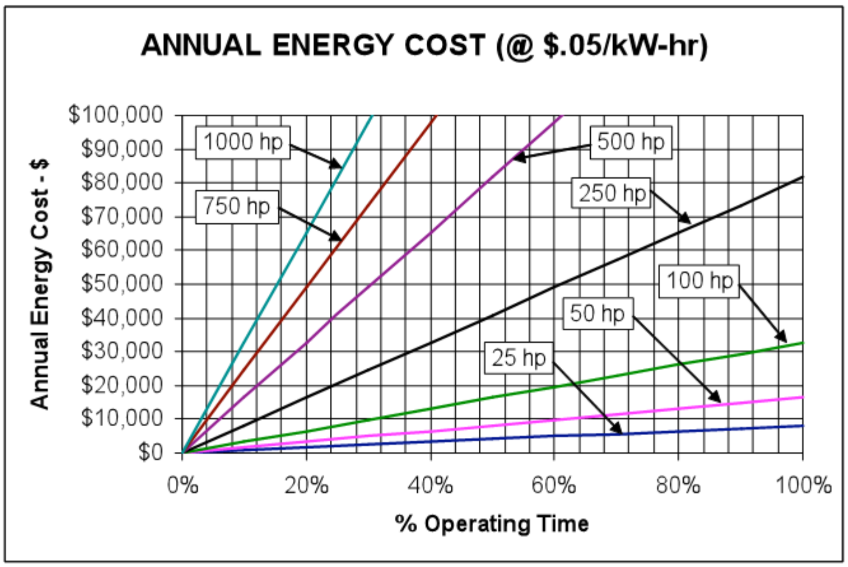


Figure 1: Annual Pump Energy Costs [1].

Most pump systems running today have significant operational costs because they use constant speed centrifugal pumps. According to Minett [3], about 80% of the pumps in the world still are constant speed units. Constant speed centrifugal pumps, in certain applications, can be extremely expensive to run for many reasons. One reason is the fact that, in most applications, the motor is always running at its maximum speed, not allowing it to reduce its power consumption level during its operation. Also, as a protection for low flow demand, i.e., deadheading, for these constant speed centrifugal pumps, it is necessary to include recirculation pipelines routed to either an upstream reservoir or back to the suction intake of the pump. This approach is also costly due to the amount of extra piping that is needed in order to run the system [4].

Another expense that exists while working with constant speed pumps is that of control valves that are necessary to control the flow of liquid being provided to the system. The control valves are normally installed on the discharge line in order to control the amount of liquid that should be delivered to meet the needs of the process, since, most of the time, constant speed pumps without a control valve provide a flow higher than what the system being supplied with liquid normally requires [5]. Figure 2 shows how a constant speed pump running at 3,450 rpm has its flow affected when a control valve varies the system's friction head:

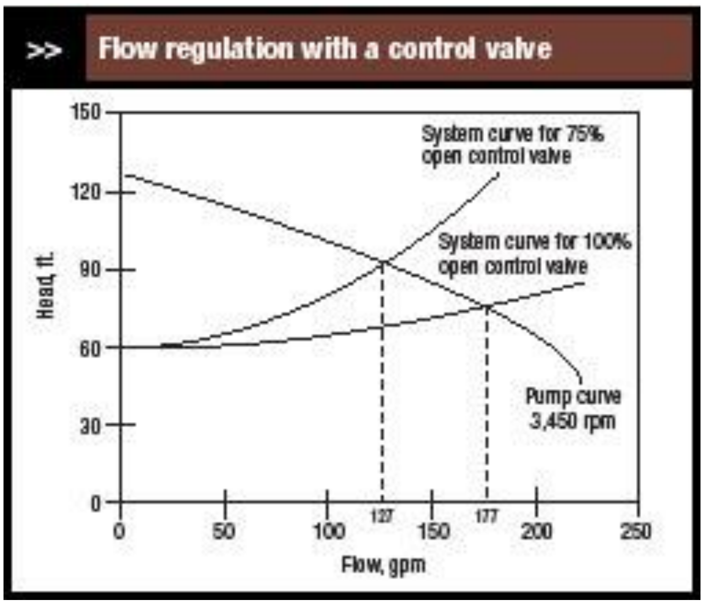


Figure 2: Flow regulation with a control valve [5].

The valve then provides a pressure drop in the system that is equivalent to the difference between the pressure supplied by the constant speed centrifugal pump and the pressure required by the process. This method causes the apparent system curve to be steeper; however, it still crosses the pump curve at the required operating point of the process. This valve pressure drop causes a major loss in pumping energy as well as a lower pump efficiency. Therefore, pumps have to work in a less efficient region once the system is throttled by a control valve, moving from its natural state, e.g., 80% efficiency, to its throttled and less efficient state, e.g., 72% efficiency, once the valve is installed in the system, as shown in Fig. 3 [6].

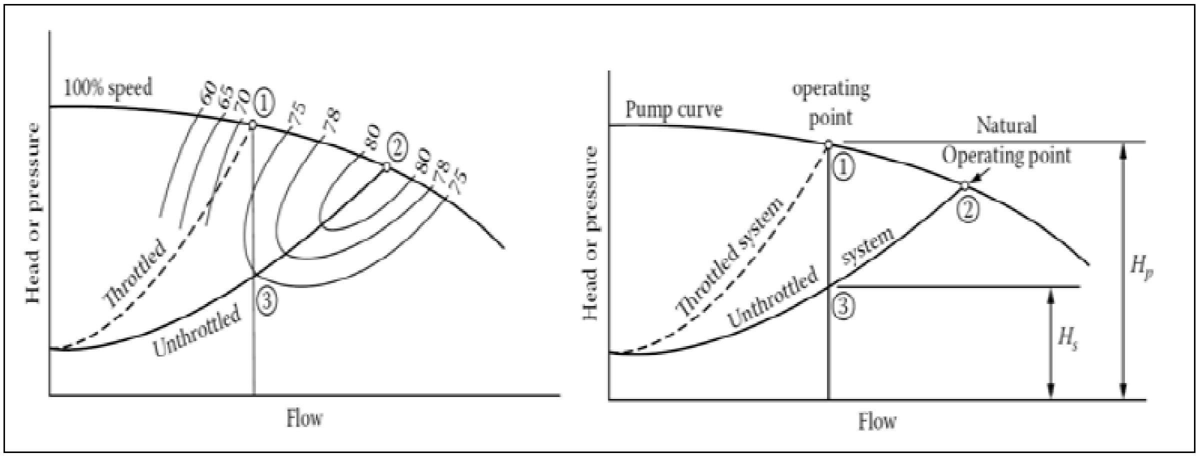


Figure 3: Control valve throttling and pump efficiency [6].

Control valve throttling is necessary because the valve must reduce the flow of the liquid based on the system's liquid requirement since the pump is providing a greater flow based on its constant speed. Even though the constant speed pump is running at a less efficient state, Pelikan [7] points out that, in very large conventional systems, the pump also has a reduction in horsepower when the flow is decreased by a control valve, hence, requiring less energy to run it. However, even though these energy savings are appreciable, they are not as high as what variable speed pumps could provide. Therefore, this shows how a constant speed pump can be wasteful due to the necessity of having a control valve, since the equipment necessary to manage these control valves can also be seen as another aspect that has increased power expenditure.

In order for the control valve to respond to the flow requirements of the system, the installation of a level sensor is required. Normally a standing pipe is installed next to the liquid reservoir, e.g., a deaerator tank in a steam power plant, which would have the same liquid height as the reservoir. In this standing pipe, a float level device is installed and connected to an air compressor. Based on where the float is, this air compressor will either increase or decrease the amount of air being supplied, i.e., the higher the level of the liquid, the more air will be supplied by the compressor. This pneumatic control changes the control valve, regulating the flow of water into the reservoir, where the higher pressure and air supplied by the compressor will cause the valve to close more. For this reason, the air compressor always has to be on, spending more energy to control the flow of liquid in the system as well as higher costs to acquire additional materials such as air supply lines, flanges, reducers and isolation valves to properly integrate the air compressor and the control valve [6].

Also in most systems, both a control valve and recirculation lines are necessary. Recirculation lines are needed for two reasons: (i) to maintain some flow through the pump and to avoid dead-heading on the flattest part of the pump curve, (ii) to allow the excess flow of liquid provided by the constant speed pump to go back to its storage tanks when the system demand is low. Again, this can be a very costly method due to the energy lost from the pressure drop created by the control valve and the flow being recycled. It is also known that, due to the amount of equipment necessary to run the control valves, the risk of mechanical issues is increased, and these devices have a record of being in the maintenance shop more than any other control device [6].

Because of the costs and losses that exist in running constant speed centrifugal pump systems, more effective ways are needed to keep pumping systems running with the lowest expenses and losses possible while maintaining reliability. For this reason, the implementation of variable speed pumps in certain applications can be advantageous as compared to constant speed centrifugal pumps [8, 15]. This document will explore that comparison in a steam power plant application.

1.2 Variable Speed Pumps

When discussing pump systems and their respective costs, the entire pumping system, which includes the piping, fittings and valves, must be taken in consideration. Also, it must not be forgotten that the way the pumps are operated can highly impact the overall energy consumption. There are several ways that pumps can be operated, such as using single or multiple pumps so that they can be run in parallel or in series in order to improve the efficiency of the system. However, in order to minimize power consumption, the pumps should run at their most energy effective flow rates and pressures. Since this project is focused on comparing variable speed pumps with constant speed pumps, Pump Energy Effectiveness (GPM/kW) could be considered as a useful method to compare such pumps in specific systems [8].

Variable speed pumps have their highest energy effectiveness at lower flow rates and over a range of flow rates, but not at their maximum flow rates [5]. Constant speed pumps, on the other hand, have their highest energy effectiveness at their maximum flow rates [8]. This shows that variable speed pumps can be more advantageous in cases where lower liquid flows are required, i.e., have them installed in a small irrigation system rather than in a city water plant. An important factor to consider is that the flow rate at which the pump operates in its performance curve depends on the location at which the pump head-capacity curve and the system curve intersect, termed the system operating point (Fig. 4). The pump head capacity curve relates the pump's flow, head, and speed, while the system curve relates the head and flow through all elements in the path of the fluid flow excluding the pump. The elements that determine this curve are the static head, i.e., the difference in head across the system when the flow is zero, including pressure and hydrostatic head; and the friction head, i.e., the losses in pipes, valves, expansions, contractions, elbows, and couples – any component through which fluid flows [5].

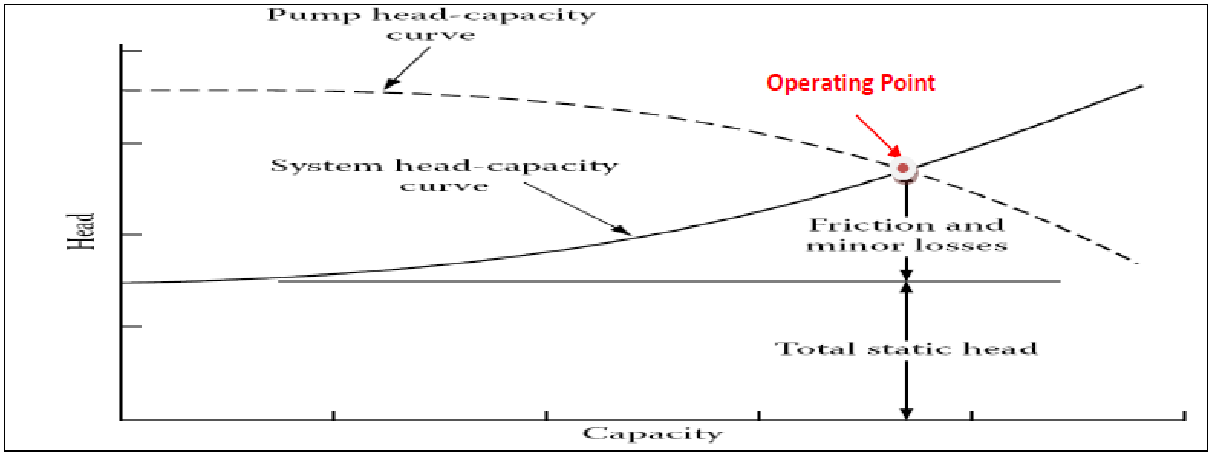


Figure 4: System curve, showing pump curve, system head capacity curve and operating point. "Head" is related to pressure and "Capacity" is related to flow rate [6].

Because the total head loss is due to total static head as well as friction and minor losses in the system, in order to compensate for such losses, many plants waste power by over-sizing constant speed pumps, resulting in excessive margins in both capacity and total head [8]. Of course, some margin should be included in order to compensate for wear and slight system demand changes, which will eventually reduce the effective pump capacity. However, it is not wise to invest too much in over-sizing pumps since that will increase costs in the long run. The pump systems should also be thoroughly assessed so that the true system requirements are determined [9]. In certain systems where multiple pumps are in operation, the operating pressures, as well as flow rates of the pumps, can be set higher than needed. Furthermore, one or more of the pumps could be turned off while not compromising the process when the demand is low [9].

When using variable speed pumps, the system curve is fixed, but the pump curve shifts based on the pump's speed, as shown in Fig. 5 [5]. The acronym VSD (Variable Speed Drive) in Fig. 5 is one of the ways that variable speed pumps are referred to in the field. The VSD is the controller inside the pump that allows it to have variable rotational speeds.

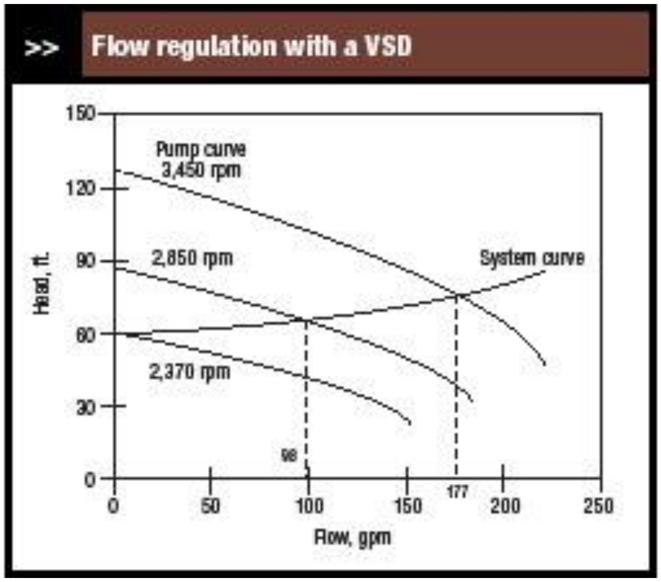


Figure 5: Flow regulation using variable speed pumps [5].

It is important to note that, for the specific example in Fig. 5, only pump speeds greater than 2,370 rpm will provide flow through the system. So it is important to choose the size of a variable speed pump based on the minimum and maximum flow rates over which the system will operate, thus guaranteeing that the pumps will meet the full range of flows required by the system.

By using variable speed pumps as a method of supplying the necessary flow for a given system, due to their controllers, less equipment, e.g., control valves, may be needed as compared to those for constant speed centrifugal pumps. The system will still require a level sensor that is continuously transmitting information to the pump; however, the use of control valves and recirculation lines will no longer be needed. This is because the variable frequency drive pumps, which will have reservoir liquid level information, will only supply the necessary flow to maintain the desired reservoir level. That can eventually result in energy savings since the pumps will not be running at maximum speed at all times as do the constant speed pumps, potentially reducing the overall loss of energy which would be used by the constant speed pumps. Also, not having a control valve to manage the flow of liquid being supplied could yield significant savings since the expenses of some pieces of equipment and the energy needed to run the control valve will no longer be incurred [4].

A study performed in Germany by Hellmann [10] at a seawater desalination plant showed great energy savings using variable speed pumps as compared to constant speed pumps which use control valve throttling. According to Hellmann, variable speed pumps offered advantages for that application such as fully automatic start up and shut down; but most importantly, reduced energy consumption. This was achieved because the variable speed pumps operated at their optimal point, i.e., desired discharge pressure and flow rate, without having throttling losses in pressure and flow control valves that come with constant speed pumps. Also, the control valves not only produced pressure and flow loses in the system, but they also caused the plant to have higher power consumption (5870 kW for constant speed pumps versus 5325 kW used by the variable speed pumps). As a result, by being able to get rid of the control valve throttling loses when using variable speed pumps, this desalination plant was able to save approximately US$261,600 per year in electricity costs (at six cents per kilowatt hour) [10].

In Italy, research was performed on two on-demand irrigation systems that were served by an upstream pumping system. The focus of this research was to analyze possible energy savings when using variable speed pumps to serve these irrigation systems instead of the existing constant speed pumps. According to Lamaddalena and Kila [11], the irrigation system (i.e., pumping station as well as the irrigation network) was designed to meet the peak irrigation demand which varied often during the irrigation season; and peak demand was normally limited to only a few days. For this reason, the existing pumping station, which used constant speed pumps, was oversized during most of the irrigation season. This meant that, during the off-peak periods, the constant speed pumps provided a much higher pressure head than the irrigation system required, while the flow was regulated by the use of control valves. Also, the energy consumption of these pumps dominated the total life cost of the system, reaching almost 90% of the total life cost. Taking all of this into consideration, installing variable speed pumps, and by adapting the characteristic curves of these pumps to the characteristic curves of the irrigation network, this research showed that they were able to have energy savings of 27% in one irrigation system and 35% in the second system, as compared to the energy usage of the constant speed pumps previously used by both on-demand irrigation systems [11]. Therefore, this research was able to show another application in which variable speed pumps were a better choice as compared to constant speed pumps due to the low flow and low pressure normally needed by the system.

In Queens, New York, the state's Department of Environmental Conservation (DEC) had mandated in 2010 that the Astoria Generating Co. replace its constant speed pumps with variable speed pumps on three of the operating units. However, the company was mandated to do that, not because of energy saving reasons, but for environmental reasons. That was because a great flow of water from the East River in Astoria passed through the plant annually in order to cool it down, and the DEC wanted that flow to be decreased in order to reduce "impingement and entrainment of aquatic organisms and minimize environmental impacts" [12]. This just shows an example in which energy savings was not a priority when choosing to implement variable speed pumps. As a result of this mandated modification, a reduction in the flow of water going through the Astoria power plant by using variable speed pumps was achieved, allowing the company to dramatically decrease the environmental impact previously caused by constant speed pumps.

Even though several studies have shown that the use of variable speed pumps can be the best method to save energy in pumping systems, some research has shown no significant energy savings when using variable speed pumps. In Hong Kong, experiments were conducted using a simulated virtual environment, i.e., a computational model, which represented a super high-rise complex building central air-conditioning system being constructed in the city. The simulation used: (i) constant speed pumps (in addition to control valves and recirculating pipelines) for the chillers and heat exchangers in two sections of the building and (ii) variable speed pumps to distribute water to terminal units in two other sections of the building. The speeds of the variable speed pumps providing water to the terminal units were controlled in such a way that a *fixed differential pressure* was maintained between the chilled water supply and return pipelines and at the critical points. However, according to Ma and Wang [13], this strategy was not optimal since power consumption was not affected significantly. This was due to the fact that the chosen *fixed differential pressure* affects the total number of operating pumps, i.e., more pumps were required to operate in order to maintain the *fixed differential pressure*, which then affected the power consumption of the system.

Because of this, Ma and Wang conducted simulations involving variable speed pumps using: (a) *fixed differential pressures* as well as (b) *optimal differential pressures* in which the latter introduced a pressure optimizer into the pump system. When analyzing the *fixed differential pressure* strategy to maintain a constant pressure with a changing flow, a partially closed control valve had to be introduced in order to increase flow resistance so that the desired pressure could be maintained. This caused an increase in wasted energy at medium-load and low-load conditions resulting in power consumption not being reduced significantly in comparison with the results obtained using constant speed pumps.

In the strategy considering *optimal differential pressures*, it was shown that the differential pressure could be lowered as the load was reduced, which minimized the flow resistance in the system, eventually reducing the power consumption of the variable speed pumps. It was concluded that the energy savings predicted using the *optimal differential pressure* strategy was relatively small (1% to 5% difference in power consumed) as compared to the results predicted using a constant speed pump system. It was also concluded that, for this application, the only way that substantial energy savings would exist, would be to implement a third strategy: (c) *optimal pump speed control with optimal pump sequence control* (i.e., creating a control system that would allow the pumps in parallel to switch on and off automatically based on the pumping needs in order to supply the desired pressure to the system). It was shown that when implementing this strategy, the building could have energy savings of 12% to 32% (depending on the time of year) as compared to the constant speed pumps approach. Excluding this third strategy, the use of constant speed pumps (in addition to control valves and recycling pipelines) would meet the pressure and flow requirements of the system with a power consumption similar (within 1% to 5% difference) to that of variable speed pumps [13].

The company Cycle Stop Valves, Inc. affirms that, when you compare variable speed pumps to constant speed pumps that are correctly sized for a specific application, the variable speed pumps will actually burn/waste energy. If that is not enough, variable speed pumps can cause many negative side effects on the system as compared to standard constant speed pumps [14]. An example was provided by Austin [14]. A specific system required 1200 GPM (gallons per minute) for the first 12 hours of the day and 100 GPM for the next 12 hours of the day (both having the same 231 feet of head) at 10 cents per kWh. When running the constant speed pumps for the first 12 hours, i.e., 1200 GPM and 231 feet of head, the pumps used 100 HP in comparison to a usage of 103 HP when running the same scenario with variable speed pumps. This extra 3% to 5% of power was due to energy use by the pump's drive, i.e., the computer, and loss of efficiency for having the motor run on pulsing DC voltage [14].

For the next 12 hour shift (100 GPM and 231 feet of head), the constant speed pump with the use of a control valve used 42 HP, while the variable speed pump used 38 HP by decreasing its speed from 3550 to 3280 RPM. However, by taking in consideration the 3% of extra energy consumed by the variable speed pumps' computer, this increased the power required to about 39.14 HP. Therefore, according to Austin, "at 100 GPM using 38 HP, the variable speed drive is burning about 4.56 times more energy per gallon of fluid moved than when the pump is running at constant speed at 1200 GPM". Finally, he acknowledged the fact that pump control valves will also waste energy in a system; but the difference between the wasted energy of control valves running at the best efficiency point to the energy wasted by the variable speed drive was minimal, i.e., US$29.69 in energy wasted by variable speed pumps as compared to US$30.18 in energy wasted when using constant speed pumps [14].

Austin also pointed out that variable speed pumps can provide the system with pulsing DC voltage, EDM currents, critical speed vibrations and radio frequency interference. These issues could cause the early destruction of the pumping system, requiring early technical assistance for repairs [14]. Therefore, if one is able to choose the correct constant speed sizes and control valves for the specific application, one can actually be saving money as compared to the installation of variable speed pumps in certain situations.

Many buildings are not able to replace the constant speed/volume pumps by variable speed pumps because of a schedule or a budget constraint, since variable speed pumps can have a very high initial cost. This was the case of a hospital in Rochester, New York that wanted to replace the HVAC centrifugal chiller that was originally installed in 1977. The two centrifugal chillers were replaced in 2002; however, due to budget constraints, the existing constant speed pumping system was not replaced [15].

This pumping system consisted of: (i) two identical 40 HP chilled water pumps, which were base-mounted end-suction pumps rated for 960 GPM at 84 feet of head; (ii) two identical 60 HP condenser-water pumps, with a vertical split-case centrifugal pump rated for 1,300 GPM at 120 feet of head. These two condenser pumps were constant volume, and one pump operated at a time. In this system, both of the chilled water pumps would run whenever a chiller operated, and one condenser water pump worked continuously. A variable speed drive was installed on one of the centrifugal chillers so that, when that chiller was fully loaded for a period of time, the load could gradually be shifted to the second chiller causing them to operate at part load with the variable speed drive. By retrofitting the chillers with the new technology of variable speed drives, the hospital was able to save 491,671 kWh in annual energy consumption, i.e., $58,873 in annual energy savings [15]. Therefore, this study showed that, by keeping the constant speed pumps (due to budget constraints) in the HVAC system of the hospital and just retrofitting the centrifugal chillers with variable speed drives to distribute the load among the chillers, the hospital was still able to have major energy savings after the replacements.

Finally, the Affinity Laws [16] describe what happens when the speed of centrifugal pumps change (refer to Appendix A for a list of the Affinity Laws). Since the second Affinity Law states that the pressure drop is proportional to the square of the flow speed, this implies that one should only consider using variable speed pumps in systems that have loads constantly varying from a low pressure, low flow operating points to high pressure, high flow operating points. Therefore, situations in which variable speed pumps should not be used include when a system requires most of the pressure and flow that the pump can produce most of the time. Also, variable speed pumps use computers; so installing them in places with very high ambient temperatures can be costly, since the installation of AC cooling systems might be necessary in order to maintain the ambient temperature within a computer's working temperature range [16].

1.3 Life Cycle Cost Analysis

Whenever dealing with new projects, one could be faced with multiple cost-effective alternatives to choose from. So that the different alternatives can be easily compared for the most cost-effective solution to be chosen, a life cycle cost analysis approach is commonly used. The life cycle cost (LCC) can be defined as "the total cost of ownership of machinery and equipment, including its cost of acquisition, operation, maintenance, conversion and/or decommission" [18]. For many new projects, procurement costs, i.e., equipment cost, may be the only costs used to select systems and equipment when checking the length of the payback period; but this approach considers a relatively small part of the total life system cost. For this reason, life cycle cost analysis is important to demonstrate whether or not savings will also exist in the operational costs in order to justify the investment costs. In most cases, life cycle cost analysis is used as a tool to compare the costs of different approaches so that the lowest cost and most feasible approach can be selected for the completion of a project [18].

There are multiple methods for performing an extensive life cycle cost analysis, varying from building spreadsheets from "scratch", e.g., Microsoft Excel, to software that has been developed to assist users with the input of the variables existing in the project [19]. The United States Department of Energy (DOE) provides a piece of software called, Building Life Cycle Cost [20], which gives computational support for the analysis of capital investments in buildings. DOE's BLCC software will be used as the primary tool to construct the life cycle cost analysis for the project at hand.

The study period used in life cycle cost analysis can range from twenty to forty years, depending upon the project to which it is being applied (e.g., for pumps' life cycle costs, a study period of twenty years is commonly used). Since LCC deals with lengthy study periods, when performing these calculations, present value, future value and inflation must all be taken into consideration. The software provided by the DOE already takes all of these values into consideration once the user inputs the project's costs into the software; and DOE updates the inflation and escalation rates used by the software at the beginning of every fiscal year (October 1st) so that present and future values are calculated accurately [20].

Since pumping systems account for about 20% of the world's energy used by electric motors [6] and between 25% and 50% of energy usage in certain industrial facilities [6], it is very important to perform a life cycle cost analysis in order to be sure that the most cost efficient pumps are being used in a given application [6]. The life cycle pump costs must include the total life-time costs to purchase, install, operate, maintain (taking account of any associated downtime, as well as support equipment, environmental costs due to contamination from pumped liquid), and decommission the equipment [22]. With that taken into consideration, Eq. (1) can used to calculate the life cycle cost for pumping systems, together with all of its elements [20].

Elements of the Life Cycle Cost Equation:

$$\mathbf{LCC = C_{ic} + C_{in} + C_{e} + C_{o} + C_{m} + C_{s} + C_{env} + C_{d}} \qquad (1)$$

The nomenclature defines all terms in Eq. (1), ranging from initial costs to decommissioning costs. In a specific application, not every single element might be used or needed. However, to start a LCC calculation for pumping systems, all of the above elements should be taken into consideration. Once all costs discussed previously are determined for all desired pumping system alternatives, the inputs can be used in the U.S. Department of Energy's life cycle cost software (BLCC or any other analysis software preferred by the user). By doing this, the future values (i.e., costs for the years to come in the life of the system) can be calculated using the correct inflation and price escalation percentages (as determined by the U.S. government) and converted into present value costs for easier comparison of the costs from each alternative. Once the LCC values are obtained, the project manager can then determine which would be the most cost effective alternative to select for a given project [20].

Therefore, in order to determine whether constant speed pumps or variable speed pumps are the best option when discussing cost effectiveness for the project at hand, an approach similar to that of Eq. (1) will be used so that the best option can be selected.

1.4 Scope of Work

In this work, two “BoosterpaQ® Hydro MPC CRE 15-3” variable speed pumps (refer to Appendix B.2 for pump curves and specifications) provided by Grundfos Pumps Corporation were installed in the steam power plant building located on the University of Kansas Lawrence campus. The pumps are shown in Fig. 6.

Figure 6: BoosterpaQ® CRE 15-3 Variable Speed Pumps.

These pumps were installed in order to be compared to already existing Worthington D-824 constant speed pumps being used in the power plant (refer to Appendix B.1 for pump curves and specifications) shown in Fig. 7.

Figure 7: Worthington D-824 Centrifugal Constant Speed Pump.

An ONSET HOBO [27] data acquisition system was used to acquire data for both types of pumps. The pumps normally are required to provide condensate water for two different areas of the power plant, and for that reason they are referred to as condensate pumps. The first area is the boilers' feedwater deaerator tank #2 located on the basement floor of the power plant where the condensate pumps are also located. The deaerator tank has three main functions in the power plant:

(i) As the name already says, it removes entrained air from the water, often times called deaerator make-up water, provided by the pumps. It completely removes the entrained air from the water going into the boilers through the use of perforated metal trays that mix the water with steam and oxygen scavenger chemicals in order to avoid corrosion of the boilers;

(ii) Preheats the water through the contact that the water has with the steam, so that boiler efficiency is increased;

(iii) It stores the “air reduced” water so that the boilers always have a supply of hot deaerated water to meet the system’s demands [26]. Figure 8 shows a basic schematic of a tray-type deaerator tank similar to the one used in The University of Kansas’ Power Plant [24].

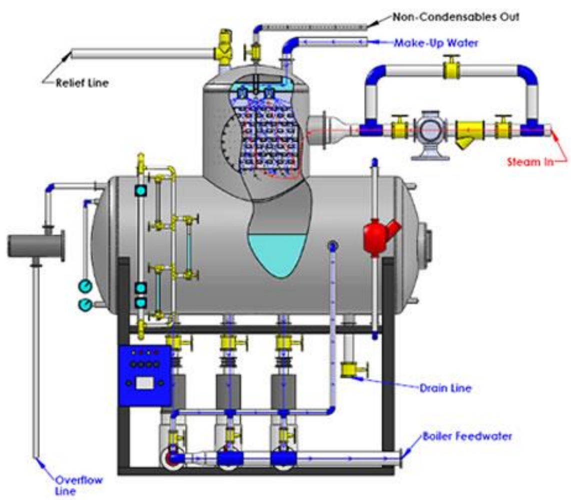


Figure 8: Tray-Type Deaerator Tank [24].

The second area to which water is supplied is a heat exchanger located on the top floor of the power plant which was installed only a couple of years before the start of this project, i.e., 2011 (see Fig. 9 for a schematic of the power plant). This heat exchanger has two functions: (i) the steam that escapes from the deaerator tank, instead of just being released into the atmosphere, goes through it and condenses by interacting with the cooler water provided by the pumps, so that it can be reused as part of the water that goes into the deaerator tank, avoiding the purchase of that amount of water from the city; (ii) the interaction of the water with the steam causes the water to heat up, increasing the efficiency of the plant, since it has to use less energy to heat up the water located in the storage tanks that will be sent to the deaerator tank and used by the boilers. Therefore, given the scenario of the application, three test cases were taken into consideration in order to provide a fair comparison between the variable speed pumps and the constant speed pump. The fourth case was not considered to be a fair comparison. In that case, the constant speed pumps were supplying much more water flow to the system than the variable speed pumps. For this reason, the first three cases are emphasized more than the fourth case.

Case 1:

The variable speed pumps were configured to work with a constant discharge pressure in order to mimic the operation of the constant speed pump, supplying water to both the feedwater deaerator tank as well as to the heat exchanger. In this case, the flow of water required by the power plant's demand was still regulated by the control valve when running both the variable speed pumps and the constant speed pump.

Case 2:

The variable speed pumps were again configured to meet the water demand using a constant discharge pressure in order to mimic the work of the constant speed pump. However, in this case, for at least two hours of the day, both the constant speed pump and the variable speed pumps were each limited to supplying the water just to the feedwater deaerator tank in the basement of the plant. That is, the valve was closed in the line to the top floor heat exchanger. After having that data recorded, each pump ran for another hour of that day while supplying water to both the deaerator tank and the heat exchanger just like in Case 1.

Case 3:

The variable speed pumps provided the necessary flow of water required by the power plant's demand based on level control. In this case, the control valve only regulated the flow of water when the constant speed pump was providing water to the system, and was fully open when the variable speed pumps were providing the water. In this case, the water supply was available only to the feedwater deaerator tank located in the basement of the power plant. The reason why water was just supplied to the tank was to establish an equitable comparison between the variable speed pumps and the constant speed pump. When the variable speed pumps ran by level control in the deaerator tank, their discharge pressure was not high enough for the water to reach the heat exchanger on the first floor. Therefore, since the variable speed pumps could just supply water to the deaerator tank, due to their low discharge pressure when operating through level control, the pipelines to the heat exchanger were closed when the constant speed pump was in operation.

Case 4:

The pipelines to both the deaerator tank and the heat exchanger were both open in this case so that both pumps could try to supply water for them. The variable speed pumps were configured to provide the water to the system based on level control of the deaerator tank, having the control valve fully open when the variable speed pumps were running. This caused the discharge pressure of the water to be much lower than when running variable speed pumps under discharge pressure mode, resulting in the pipeline pressure being too low to force the water to reach the heat exchanger on the first floor. In that case, the excess steam provided to the deaerator tank that would normally go into the heat exchanger, was released straight into the atmosphere in order for it not to overheat the heat exchanger, i.e., no water was being sent to the heat exchanger to cool it down as well as to condense the steam.

On the other hand, when the constant speed pump was running, since its discharge pressure was much higher than that of the variable speed pumps, and the control valve was controlling the water flow into the deaerator tank, the pump was able to supply water to both parts of the system. However, as mentioned before, this case is not a fair comparison between the two types of pumps, since the variable speed pumps were just supplying water to one part of the system due to their low discharge pressure, triggering the loss of steam into the atmosphere that could be reused. On the other hand, the constant speed pump was providing a much higher flow to supply water to both parts of the system, i.e., the heat exchanger and the deaerator tank, causing the steam that was previously wasted by the variable speed pumps to be saved and reused in this case. The reason that case 4 exists and data was gathered for it, was the fact that the realization that the variable speed pumps did not supply water to the heat exchanger when running in level control mode was only noticed after ten days of data gathering following this procedure. Therefore, the power consumption of the pumps cannot be compared directly since the pumps were doing two different jobs, since the Grundfos CRE 15-3 pumps just supplied water to the deaerator tank while the Worthington D-824 pump provided water to both the deaerator tank and the heat exchanger. However, based on patterns of power consumption drops from the recordings obtained for Case 2 for the times when the heat exchanger valve was open [as compared to the recordings for the times it was closed] estimates for Case 4 will be performed in order to try to fairly compare the two pumping systems for this Case.

Life Cycle Cost Analysis:

The research and data gathering in this document made for all four cases outlined previously were used in the life cycle cost analysis (LCCA) performed for each scenario using the software provided by the U.S. DOE called Building Life Cycle Cost 5 (BLCC5) [23]. The software uses an equation similar to Eq. (1), labeled as Eq. (2), which is the primary equation used to determine/calculate the life cycle cost for each pump in every case, since it adds all of the possible costs that the plant would have with regard to the pumps from their purchase all the way to their disposal.

$$\mathbf{LCC = I + Repl - Res + E + W + OM\&R} \qquad \textbf{(2)}$$

The nomenclature defines all terms in Eq. (2), ranging from initial costs to operation, maintenance and repair costs. The software (BLCC) automatically takes into consideration present and future values as well as inflation, annual rate of increase and discount rates. The current inflation and discount rates are inserted into the software at the beginning of each federal fiscal year for the upcoming year instead of using the same rates each year. The equations showing how present values are calculated for each cost included in the software will be discussed later in this document in Section 2.5.

The project at hand uses what is termed a FEMP Analysis Energy Project, which is a life cycle cost analysis for energy and water conservation and renewable energy projects that follow the Federal Energy Management Program rules, based on 10 CFR 436 [23]. According to the U.S. DOE, this kind of analysis is to be followed primarily with regard to federally owned or leased buildings. However, the methodology used in this analysis is simply based on general economic theory that can be used in the analysis of private buildings as well as any kind of energy and water conservation project. Also, the FEMP analysis is entirely consistent with ASTM (American Society for Testing and Materials) standards on building economics [25]. For this reason, this project used the FEMP methodology for each of the four cases previously mentioned in order to assess the life cycle costs of the constant and variable speed pumps located in The University of Kansas' Power Plant, in order to determine which of the two pumping systems was the most cost effective for this specific application.

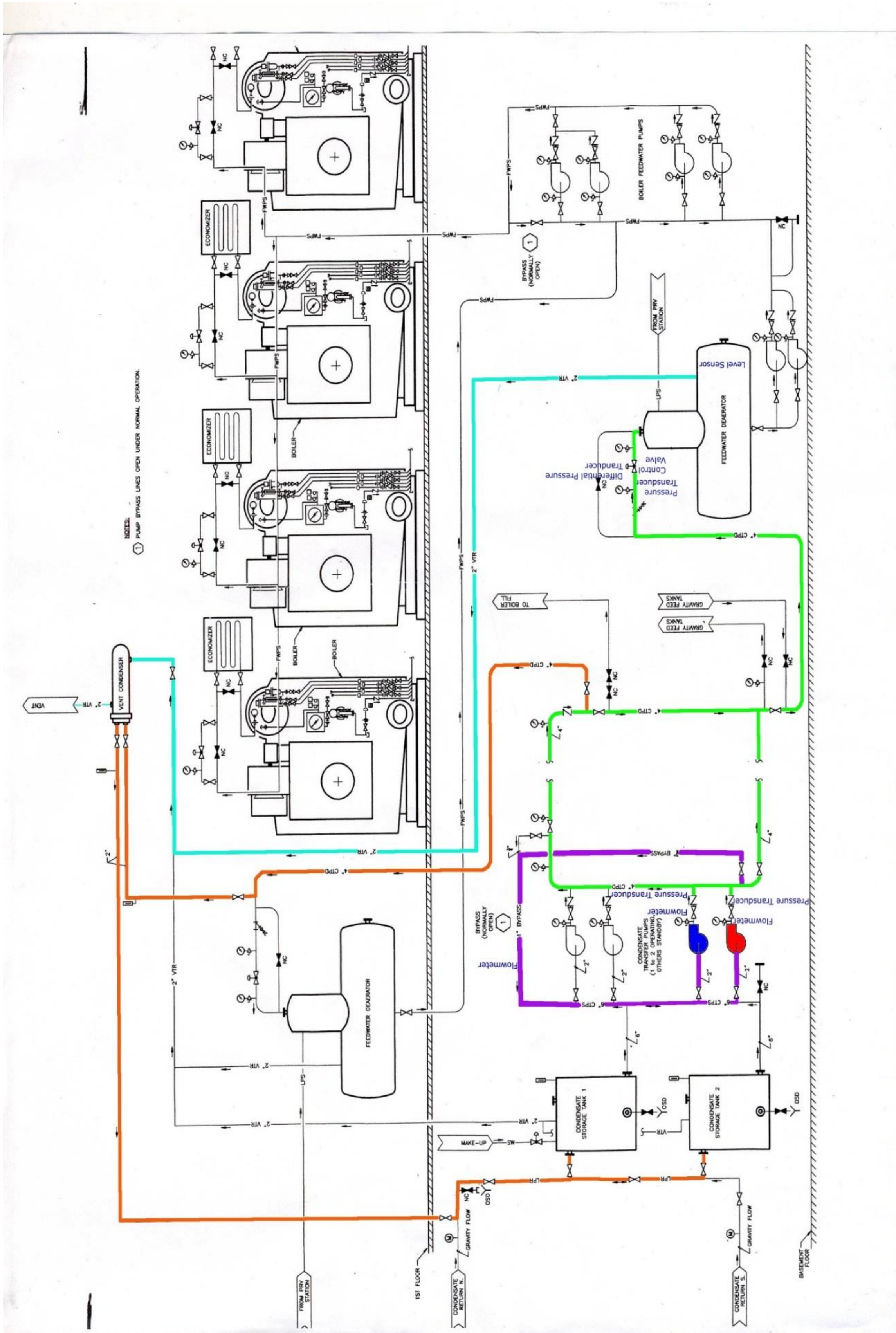


Figure 9: The University of Kansas Power Plant Schematic [26]. (Red Pump= Worthington D-824; Blue Pump= CRE 15-3; Green lines= Deaerator water supply; Light blue line= Steam line to heat exchanger; Orange lines= condensate water supplied to heat exchanger and back to condensate storage tanks; Purple lines= Bypass to return water to pumps suction side.)

Chapter 2:

2.1 Setup

The steam power plant situated at the campus of the University of Kansas was the location at which the comparison between a Worthington D-824 constant speed pump and Grundfos BoosterpaQ® CRE 15-3 variable speed pumps was made. Figure 9 shows a schematic of the layout of the power plant components [26].

When it was first built, the power plant was used to provide electricity for the University of Kansas. However, now the power plant's only function is to produce steam in order to provide hot water for buildings. The steam is also used to provide the necessary steam that the HVAC systems in the buildings around the University's campus need, and also provide heat to the buildings during the winter time. The power plant's system is programmed to have the plant maintain a constant 170 psi of steam pressure in the system. The University's campus requires a constant 90 psi of steam pressure for its HVAC systems and hot water. In order to supply that constant demand of steam pressure to the plant and the campus, the boilers need to produce from twenty thousand pounds per hour to seventy thousand pounds per hour of steam (depending on the weather and time of the year) in order to maintain those required steam pressures. Colder weather and more people on campus cause the demand on the boilers to rise in order to maintain that constant supply of steam pressure to the campus and to the power plant. This requires that more water be supplied by the condensate pumps for increased production of steam. Therefore, the pumps being compared in this thesis have their data taken mostly in cold weather and during regular University operation hours in order to compare them when they work the hardest so that the results and LCCAs show values of the system during the highest demand periods in order to determine which type of pumping system is the best approach for this application.

Including the variable speed pumps, there are a total of five condensate pumps that can provide water to the deaerator tank. The condensate pump (colored in red on Fig. 9) represents the instrumented constant speed pump, and the pump colored in blue represents the Grundfos variable speed pump system that consists of two pumps that work together. The green pipeline provides water for the deaerator tank. The orange pipeline provides water for the heat exchanger, i.e., the vent condenser, and sends that water back to the condensate storage tanks. The purple pipeline is the water recirculation line which was originally identified [to this researcher] as the only recirculation line existing in the system. Hence, throughout most of the project, this pipeline was thought to be the only line that returned excess water back to the pumps and to the storage tanks. Finally, the light blue pipeline carries the steam from the deaerator tank into the heat exchanger; and any steam that the heat exchanger cannot condense is released into the atmosphere through the vent shown. The lines that receive the condensate steam that returns from the campus (just labeled as “condensate return” to the left of the condensate storage tanks in the schematic) and the pipelines and pumps previously identified in Fig. 9, are the only pumps and pipelines that are of importance to the scope of this project, since these represent the pipelines and devices used when the plant is in normal operation mode. The only line missing in the schematic is the pipeline that sends the steam, which is not used by the deaerator tank, directly into the atmosphere without going through the vent condenser (since that does not happen for the normal mode of operation, but only happens when the variable speed pumps are running in level control mode or when the valve to the heat exchanger is turned off). That pipeline follows along the pipe labeled in light blue on the schematic.

On the discharge side of both types of pumps, a Siemens magnetic flow meter 3100 and a Siemens Sitrans Mag 5000 were installed for measuring the flow rates provided by both pumps for the system. The Siemens Sitrans Mag 5000 is the controller that is used to send the information to the data logger. The same types of flow meter and controller were also installed in the pipeline that is colored purple so that data would be available for how much water was being recirculated through that line back to the pumps and storage tanks for input to the pumps. It was initially thought that this was the only return line that the plant used to return the water which was not utilized by the deaerator tank back to the storage tanks; but this line is only used when the plant’s demand is very low in order to avoid “deadheading” in the inlet side of the pumps.

The main line that returns water back into the condensate storage tanks is the line labeled in orange that goes through the heat exchanger, i.e., vent condenser. A Danfoss MBS 3000 pressure transducer was installed on the outlet side of each pump in order to measure the discharge pressure of the water provided by the pumps. For the Grundfos variable speed pumps, this pressure transducer was used as the primary sensor connected to their controller in order to make sure that the pumps were producing the correct pressure when running the pumps in discharge pressure mode. In addition, the sensor was used for data acquisition on the discharge pressure of the water when running the variable speed pumps in level control mode. The Siemens and Danfoss sensors are labeled on the schematic in blue as Flow meter and Pressure Transducer, respectively. So that the water pressure on the suction side of the pumps could be known, a Danfoss pressure transducer was installed on the inlet side of the variable speed pumps. Since both the constant speed and variable speed pumps had the same source of water and there was minimal change in that pressure, the inlet pressure was assumed to be the same for both types of pumps.

Another Danfoss pressure transducer (MBS 3000) was installed at the inlet to the control valve located right before the basement floor deaerator tank in order to check the pressure loss in the pipes from the outlets of the pumps to the inlet of the control valve. A Grundfos Differential Pressure Sensor (DPI 0-2.5 bar) was installed across the control valve so that the pressure drop across the valve could be measured (also labeled in blue next to the control valve in the schematic). Finally, in order to be able to collect data on the power consumption of the constant speed pump, Veris Power Monitoring H8044-0100-2 current transducers with an accuracy of ±1% of the reading were installed in the power box of the pump. For the variable speed pumps, their controller automatically recorded the actual power consumption of each pump (accuracy errors were not provided by Grundfos). Thus, an extra power monitoring sensor was not required. All sensors provided 4-20 mA outputs, and required 12-24 DC voltage for operation (with the exception of the Siemens flow meters that were powered by 120 Volt AC power source). For this reason, two Mastech DC Power Supplies (HY3003D) were purchased. One was placed next to the pumps in order to power the sensors next to them, and the other was placed next to the control valve in order to power the remaining sensors. All sensors were wired using Belden 1120A 16 gage cables and connected to an Onset HOBO data acquisition system using 4-20 mA cables following the current loop wiring diagram shown in Fig. 10 [27].

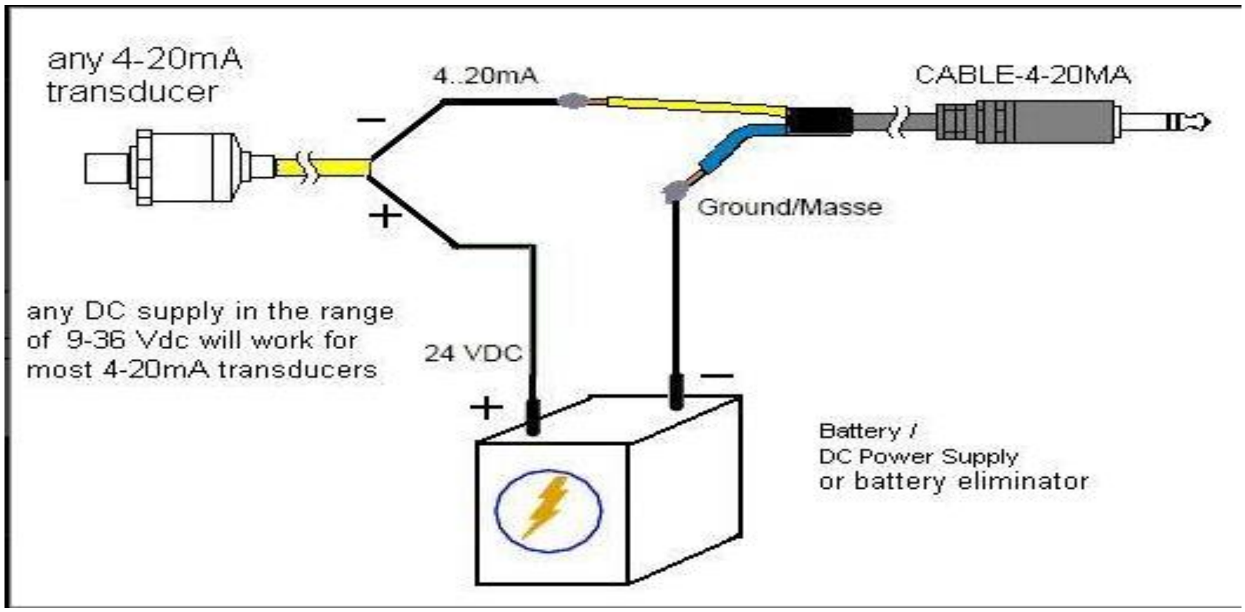


Figure 10: 4-20 mA Transducer Wiring Diagram [27].

The SureSite visual indicator and level transmitter were purchased from Gems Sensors & Controls. The transmitter was powered using one of the Mastech 30 volt DC power supplies; and its 4-20 mA output was connected directly into one of the analog inputs of the controller of the Grundfos variable speed pumps using Belden 1120A 16 gage cables. For detailed specifications and pictures of all of the sensors, data loggers, power supplies and other equipment, e.g., pressure transducers, see Appendix C.

The Onset HOBO data loggers are able to log data from any sensor that has an output of 4-20 mA, and they come with software called Onset HOBOware Pro. In the software, for each sensor that will be connected to the data logger, the values that will represent 4 mA and 20 mA can be stipulated, i.e., the minimum and maximum values that the sensors can output. Once these minimum and maximum values are stipulated, the software will automatically create a linear scaling for the given range of each sensor.

2.2 Setup and Project Challenges

Throughout the steps of this project, several challenges and problems were met and addressed. These will be explained in this document so that future studies can take them in consideration, saving time and effort, avoiding delays and similar difficulties.

The first difficulty encountered in this project was during the installation of the variable speed pumps. Normally, when installing a Worthington D-824 constant speed pump, the pipe that is connected to the header is fixed to the suction side of the pump (horizontal pipe) which is right next to its discharge side (vertical pipe) as shown in Fig. 11.

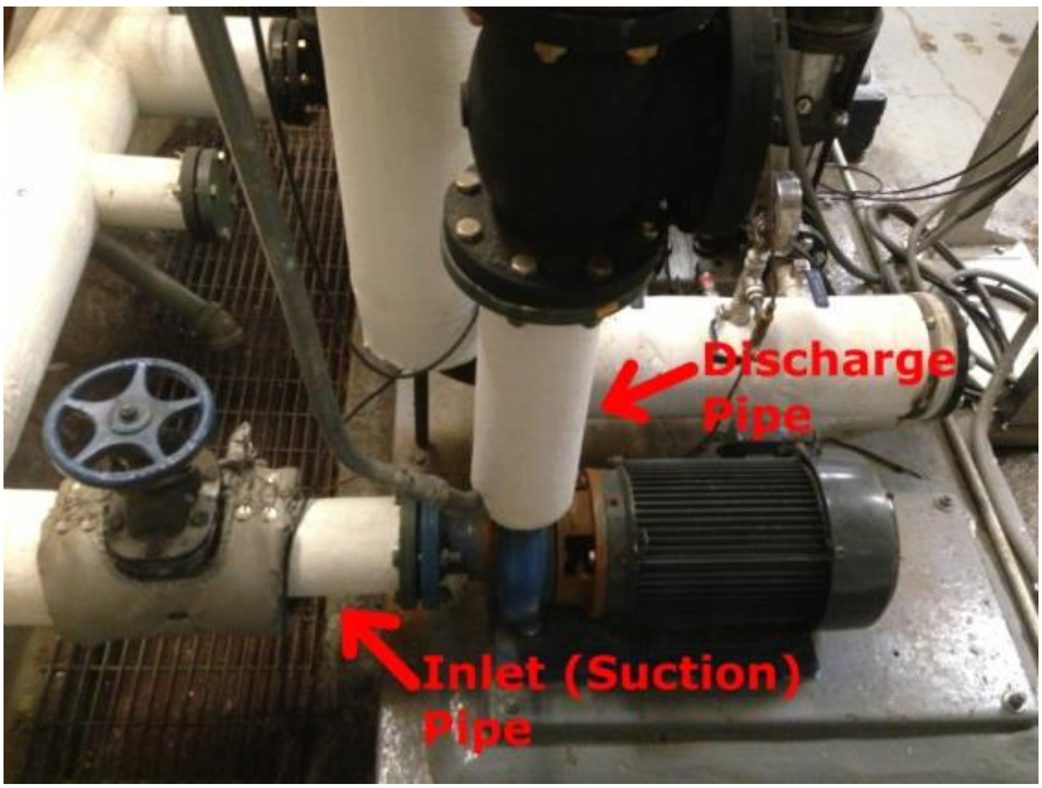


Figure 11: Worthington D-824 Constant Speed Pump Suction and Discharge Piping Connections

However, when installing the Grundfos variable speed pump system, the suction side (right side of the pumps) requires its own horizontal pipe as does the discharge side (left side of the pumps) [which is across from both pumps in the system] before it can be connected to the vertical pipes in the power plant. Figure 12 shows this pump/piping configuration.

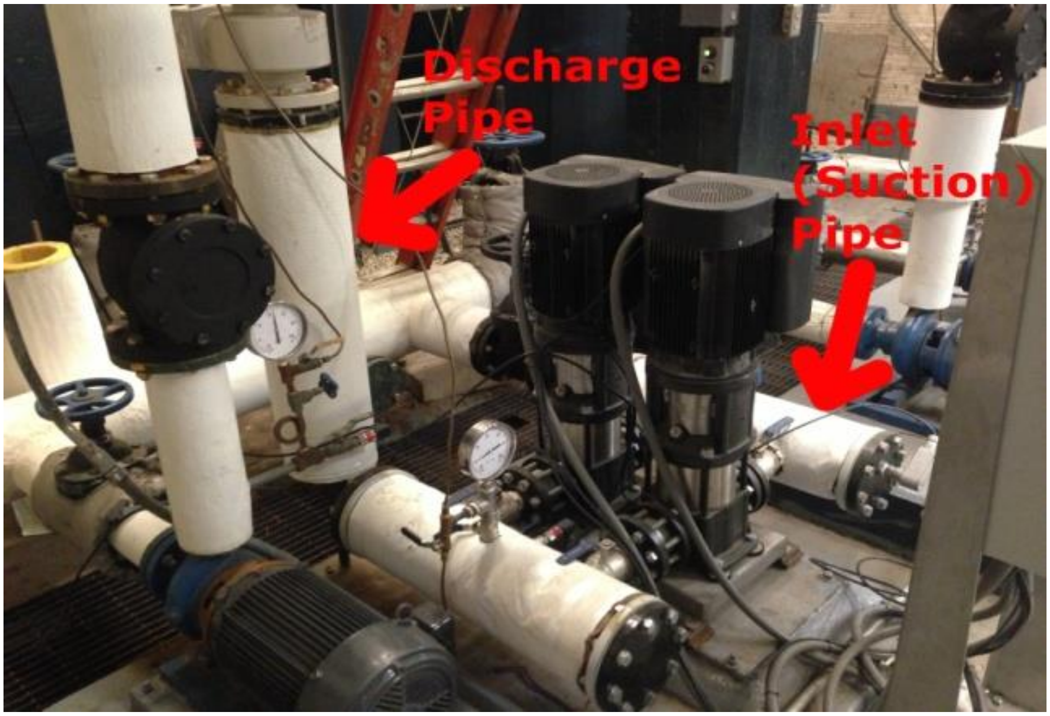


Figure 12: Grundfos Variable Speed Pumps Suction and Discharge Piping Connections

For this reason, the location where the outlet of the header was previously available to connect to a constant speed pump had to be closed and moved in order to fit the configuration of the variable speed pumps. This delayed the installation of the pumps for two weeks. This delay could have been avoided if this different configuration were known and taken in consideration prior to the purchase and installation of the variable speed pumps.

Once the pumps were installed and functioning, another difficulty encountered was choosing the type of data acquisition system to use inside the power plant. An Obvius Acquisuite Data acquisition system had been installed for a previous project at the power plant, and the first plan was to try to use that system to log the data necessary for the current project. However, the Acquisuite system used a ModBus communication protocol, which would require several converters and extra wiring to read the 4-20 mA outputs from all of the sensors used. For this reason, it was decided to purchase Onset HOBO data loggers U12-006. These data loggers were less expensive than the converters that would be necessary to convert the 4-20 mA analog outputs to Modbus protocol. They accepted any sensor that provided an analog 4-20 mA output, and worked stand alone since they were battery powered. In addition, the interface was more user friendly than the Acquisuite interface.

To collect data on the power consumption and discharge pressure of the variable speed pumps, software called PC Tools, provided by Grundfos, was used. This software was installed on a Gateway Netbook and used every time data logging was being made from the variable speed pumps. However, while the Onset data loggers collected data at equal time intervals, e.g., one data point every minute, the PC Tools E-Products software gathered data as fast as it could at random time intervals. This meant that the time between two data points could be 1 second at times or it could be 10 minutes at other times. The software was designed to gather data as fast as it could from the pumps; i.e., it does not have a setup option to choose different speeds of data acquisition, but only recording data if there were significant changes in the information chosen to be recorded. For example, if the power consumption remained the same for 10 minutes and then changed, one would see a gap of ten minutes between the last two recorded data points of power consumption. Even though this was not a difficulty encountered in the project, it is important to mention the basis of these inconsistent data taking intervals, in case future researchers question these data acquisition intervals.

The next set of difficulties were concerned with problems encountered in certain sensors installed in the system. A couple of months after the installation of the Veris Power Monitoring H8044-0100-2 current transducers, it was found that the data loggers for the constant speed pumps were gathering data that was very different from the data previously recorded for the power consumption. The transducers were returned to Veris Industries, which confirmed that the sensors had become faulty. Since they were still under warranty, a new power monitoring system was provided for the project. This delayed data gathering on the constant speed pumps for almost four months during the time of finding faulty data, shipping the item, inspecting the faulty sensor (by the company, Veris Industries) and shipping of the new sensor. This happened in 2012 during the time data was being gathered for Case 1 of this project.

There was a similar occurrence for the Grundfos Differential Pressure Sensor (DPI 0-2.5bar). Unlike the current transducers, this unit was found to be faulty and not outputting accurate data as soon as it was installed, being replaced immediately after its installation. At times when running the variable speed pumps using level control, the new differential pressure transducer was thought to be broken due to the kind of values it was outputting. However, after contacting Grundfos representatives, it was found that, since the control valve was fully open, the differential pressure across the valve was so close to zero that it caused the sensor to display small negative and inaccurate values, e.g., -0.0124 bar, which the representatives communicated to be a normal response the sensor would have at very low differential pressures which were essentially “zero” values. Section 2.5.2 of this document will provide the accuracy of this sensor for recording very low differential pressures.

In order to run the Grundfos variable speed pumps in level control mode, it was necessary to purchase and install a level sensor in the deaerator tank. Since installing a sensor directly in the tank would involve shutting off the pressurized tank, a different approach had to be found. Connected to the deaerator tank there existed what is called a standing pipe that has the same height of water as the tank. The standing pipe had a glass tube attached to it for a visual indication of the level of water inside the tank. Also, connected to this standing pipe, there were the high and low water alarms to warn the power plant workers in case either of these two situations occur. Figure 13 shows the standing pipe and the high and low alarms next to the deaerator tank located on the basement floor of the power plant.

Initially, a four-wire ultrasonic level transmitter LVU1506 was thought to be capable of sensing the water level; so it was purchased and installed at the top of the standing pipe. The way this sensor works is by creating an electronic signal that is transformed by the sensor into ultrasonic pulses that travel through the air. When these pulses hit the liquid/air interface, they reflect back to the sensor. The reflected pulses are received by the microprocessor in the electronics, and it calculates the level in the tank, outputting the information in a 4-20 mA format [28]. This information would then be sent to the variable speed pumps so that they could determine whether to provide more or less flow into the tank. In order for this sensor to work without any problems, the sensor located at the tip of this transmitter had to be always dry. However, since the project was dealing with a pressurized environment which included steam in the standing pipe, after some time, droplets of water would start to collect on the sensor, causing the ultrasonic pulses to be incorrectly interpreted by the electronics of the transmitter, sending incorrect values to the pumps’ controller. For this reason, this level transmitter could not be used in this application, since there was no way to stop droplets of water from condensing on the sensor in an environment that included condensing steam.

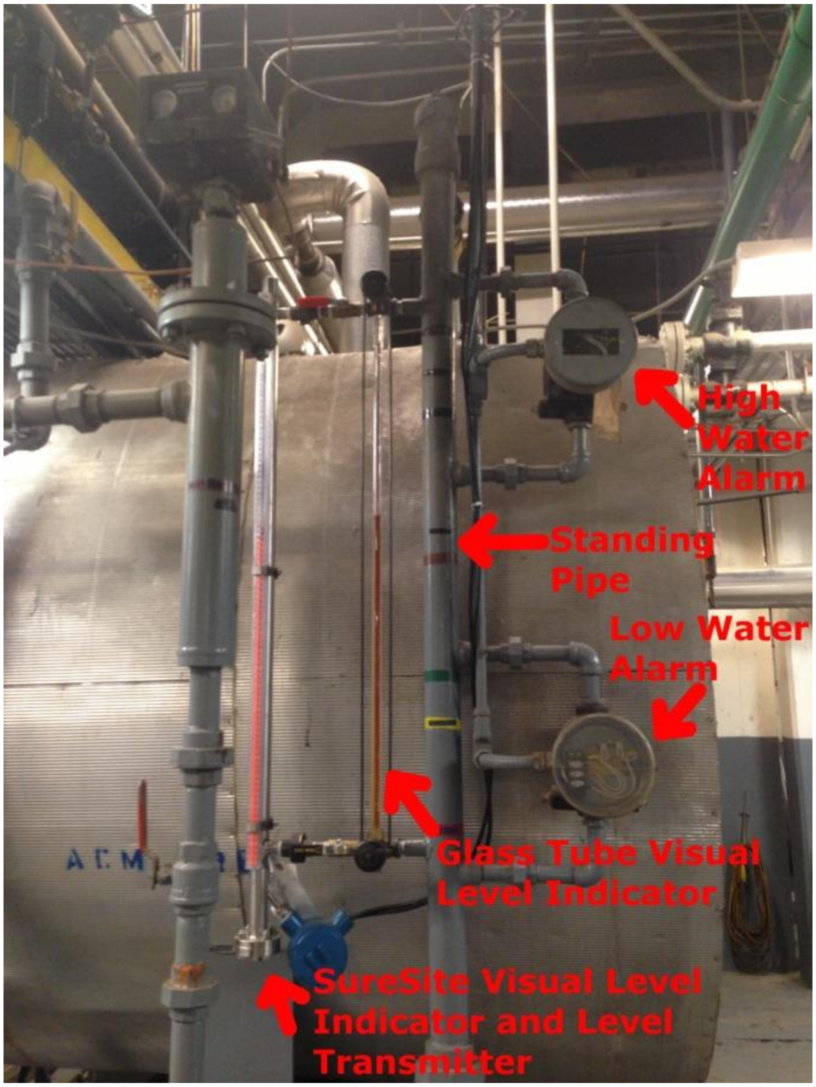


Figure 13: Standing Pipe, High and Low Water Alarms, Visual Level Indicators and Level Transmitter.

A SureSite visual indicator and level transmitter was then ordered and built specifically for this application. It was installed right next to the already existing glass visual indicator as shown in Fig. 13. The time it took from ordering to building and receiving the level transmitter was approximately three and a half months.

The SureSite sensor is powered by one of the Mastech 30 volt DC power supplies and sends a 4-20 mA output to the pumps based on where the water level of the deaerator is, being equivalent to the height of water inside the standing pipe. This sensor functions by having a magnet inside an aluminum casing that moves up and down based on the level of the water in the deaerator tank. The visual indicator consists of a pivoting "flag" assembly that has two sides with contrasting colors. As the magnet inside the aluminum casing moves up and down, these flags rotate and show the level of water inside the casing using the contrasting colors as shown in Fig. 14.

Figure 14: SureSite® Visual Level Indicator and Level Transmitter.

The same magnet inside the casing interacts with the calibrated transmitter connected to the casing and sends a 4-20 mA output to the pumps based on the level of water inside the casing [29]. The only problem encountered with connecting this level transmitter to the variable speed pumps was the fact that the pump controller did not have an option for level control input. For this reason, the 4-20 mA output of the level transmitter had to be transformed into a 0-100% signal for the pump controller, i.e., the controller interpreted the data as a percentage and not a level. Thus, the pumps had a percentage to be maintained as the set-point and not an actual water level.

A couple of difficulties were encountered when first starting to run the variable speed pumps in level control mode. The first problem was that, once the level set-point that was chosen for the pumps to maintain was satisfied or over-achieved, instead of simply reducing pump speed, maintaining a lower flow, they would enter standby mode, completely stopping the flow of water to the deaerator tank. Since this is a pressurized system, requiring a constant flow of water, this caused steam hammering in the system, i.e., the back flow of pressurized steam through the pipelines, which can cause such pipes to break as well as cause major damage to pumps' seals. For this reason, the minimum performance of the pumps had to be changed so that the pumps were continuously running to keep a minimum flow of water constantly going into the deaerator tank. Once this was adjusted, the system did not experience steam hammering again.

The controller of the variable speed pumps was not able to provide proper signal damping when running in level control mode. Whenever the level of water would go below the set-point, the pumps would speed up until the desired set-point was reached, and then slow down. However, the pumps would always go from minimum performance settings, to maximum performance settings, e.g., 40% speed to 100% speed, most of the time overshooting the set-point. This caused the curves of power consumption and flow rate never to be damped to become constant, even for constant demand by the power plant. Figures 15 and 16 show the undamped curves obtained for flow rate and power consumption when trying to run the pumps before altering the time integral setting in the pumps' computer.

When trying to adjust the time integral setting that controls the speed of response of the pumps, this caused the level to lower almost to the low level alarm; and once the pumps sped up, by the time they slowed down, the level was almost in the high level alarm of the deaerator tank. Figures 17 and 18 show the undamped curves after altering the time integral setting.

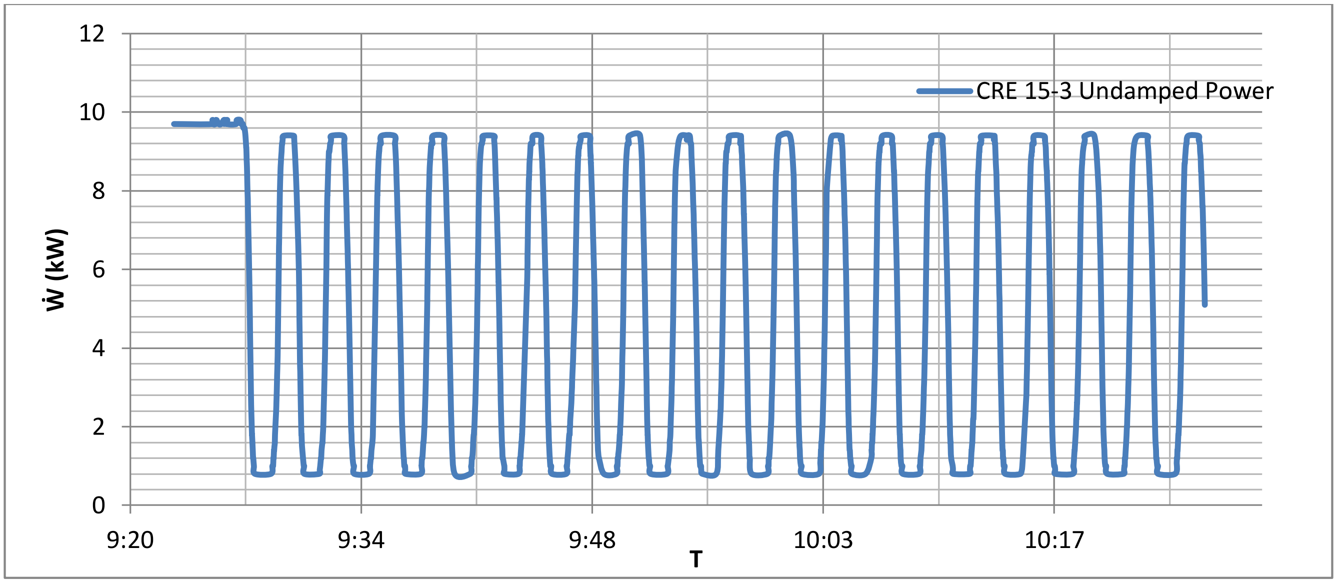


Figure 15: CRE 15-3 Undamped Power Curve (February 15, 2013).

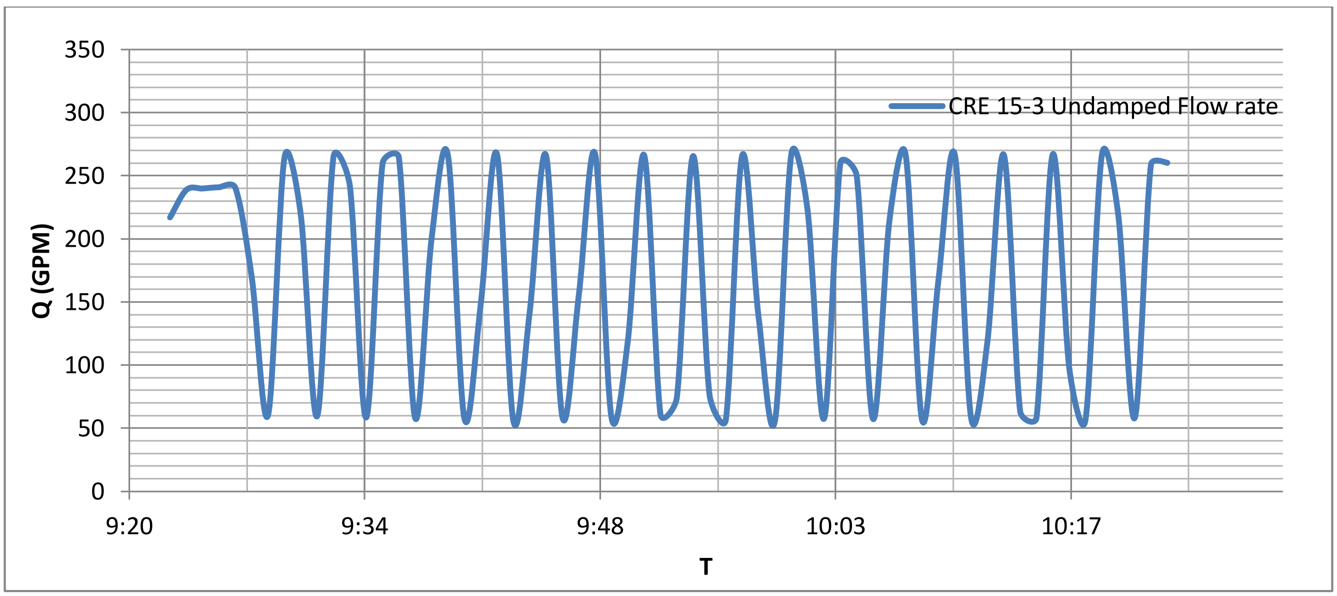


Figure 16: CRE 15-3 Undamped Flow Rate Curve (February 15, 2013).

One might not notice too much difference between the two sets of graphs, however, by comparing the two sets of graphs it can be seen that by increasing the time integral of the controller's response, the time it took for the changes of flow rate and power consumption to happen also increased, but still not causing the curves to damp.

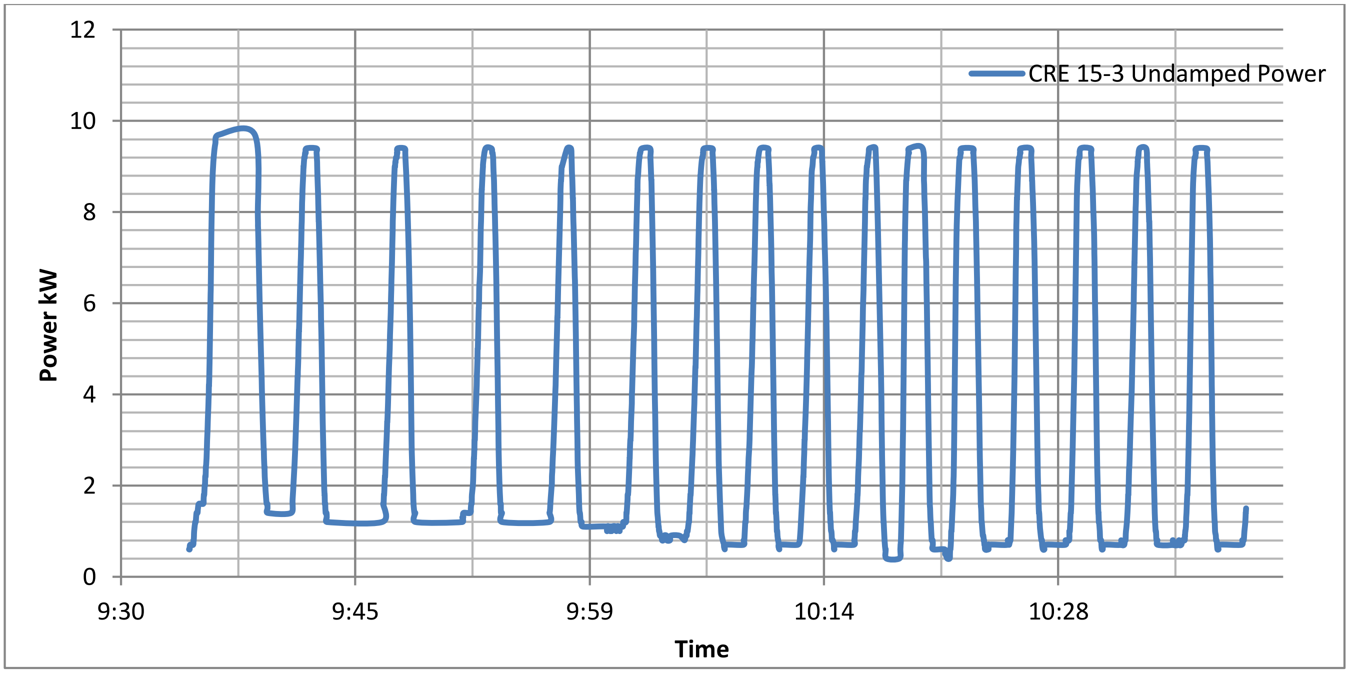


Figure 17: CRE 15-3 Undamped Power Curve with Adjusted Time Integral Setting (February 19, 2013).

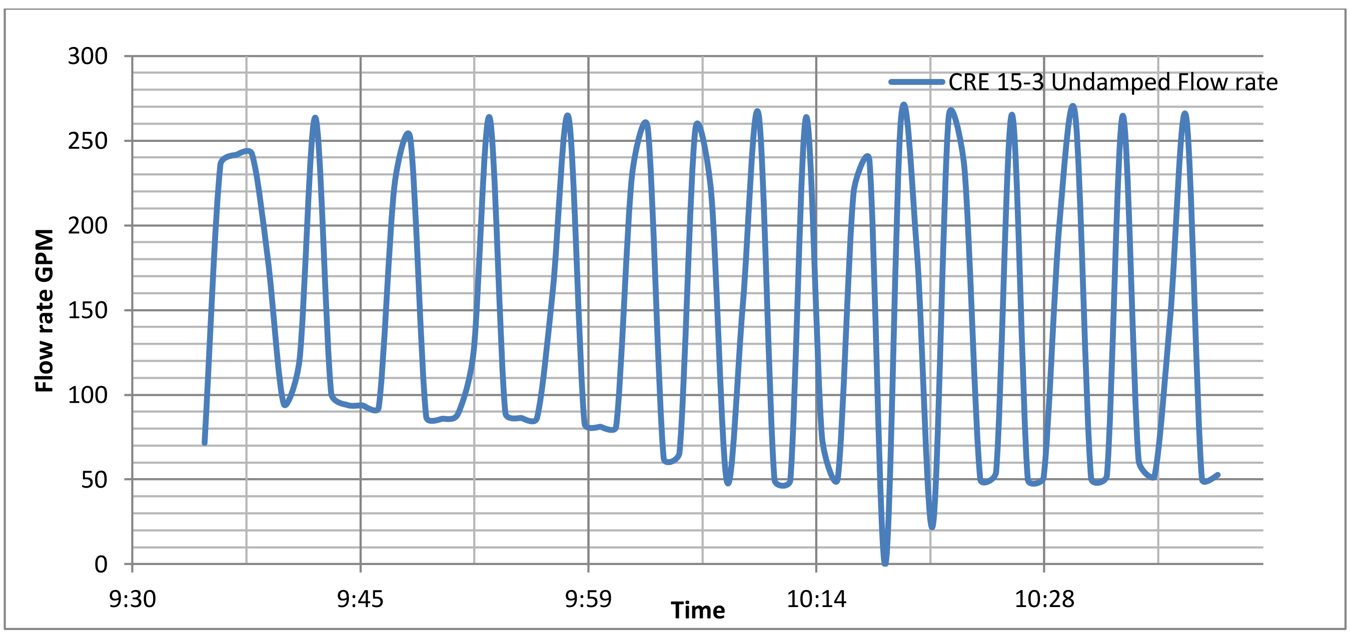


Figure 18: CRE 15-3 Undamped Flow Rate Curve with Adjusted Time Integral Setting (February 19, 2013).

This rapid change from low flow to a very high flow of water was also not beneficial for the pressurized deaerator tank, since by having the control valve fully open, it caused a great temperature shock between the water already in the tank and the water coming into it. This forced the amount of steam provided for the tank to rapidly increase in order to heat and deaerate the great flow of cooler water entering. For this reason, the minimum and maximum speeds of the pumps had to be manually adjusted in the variable speed pumps' controller with the use of a Grundfos R100 programmer in order to create a damped system curve for power consumption and flow rates and not cause a great temperature shock inside the deaerator tank. This will be shown when results/data are discussed.

After running the variable speed pumps in level control mode for a while, it was noticed that the pumps were working at higher speeds than for some of the earlier runs. After carefully analyzing the system, it was found that the check valve in the discharge line of the constant speed pump did not fully closing when the pump was shut off. This caused the variable speed pumps to provide water to the system and also backflow water through the discharge pipelines of the constant speed pumps, hence, explaining why the variable speed pumps had to work harder in order to provide water to the system. The replacement of this valve did not delay the project; however, data gathered from a couple of days (not shown in this document, i.e., first week of March 2013) had to be disregarded due to faulty check valves in the system.

Finally, when running the variable speed pumps in level control mode, the control valve next to the deaerator tank was fully open, and the discharge pressure which the pumps needed in order to provide the flow of water to the system was much lower than that of the constant speed pump for similar situations. This caused the water not to be able to reach the vent condenser which is located on the first floor of the power plant. At this point, it was found that, not only were the variable speed pumps in level control mode not able to do the same job as the constant speed pumps, but also that the main recirculating pipeline that returned water back to the storage tanks was not initially considered in the project (labeled in orange in Fig. 9). The bypass that was always thought to be the only recirculating pipeline (labeled in purple in Fig. 9), was used only when the demand of the plant was very low in order to avoid deadheading on the pumps' suction side. For this reason, three cases were added (Cases 1-3) to the project in order to equitably compare the performance of the variable speed pumps to that of the constant speed pump. The data gathering for this project started in February of 2012 when running the variable speed pumps in discharge pressure mode, and this recirculation line problem was noticed in April of 2013 when the variable speed pumps started to work using level control mode with the control valve fully open.

2.3 Test Procedure for Data Logging

For the data acquisition part of this project, different procedures were used for each of the four previously outlined cases. For this reason, it is necessary to explain how the data was logged for each individual case:

Case 1:

For the Worthington D-824 constant speed pump and the Grundfos CRE-15-3 variable speed pumps, data logging was performed for a period of six to seven days at a time, alternating the pumps being used after this period of time. In other words, information from the constant speed pump was gathered for a week, and in the following week, information was gathered using the variable speed pumps.

When gathering data for the constant speed pump, the HOBO data logger was used to log its discharge pressure, discharge flow rate, power consumption and flow rate of recirculating water in the bypass if any. All of this information was gathered at intervals of one minute between each data point for a period of six to seven days. For the variable speed pumps, the HOBO data logger was used to record the information of discharge flow rate, water pressure in the suction side of the pumps, and also the flow rate in the bypass recirculation line. This information was also stored in intervals of one minute between each data point for a period of six to seven days. The power consumption and discharge pressure of the variable speed pump was recorded using the software PC Tools E-Products provided by Grundfos, which was installed on the Gateway Netbook. As explained in Section 2.2, this information was recorded as fast as possible by the software when there were major changes in the chosen data to be logged, also for a period of six to seven days. However, the data was saved and the software restarted every three to four days in order to ensure that the computer would not freeze or lose data due to the amount of space necessary to store such information.

As explained earlier, the power plant has a total of four pump sets that provided water to the system, out of which one is the Worthington D-824 constant speed centrifugal pump being compared to second set of pumps in the system which are the Grundfos CRE 15-3 pumps. Pumps 3 and 4, which are both constant speed centrifugal pumps, were not used for the comparisons in this project, but the rotation of usage among these pumps was still performed by the staff of the power plant, where every pump was run a total of one week until the next pump was used. Also when the demand for steam was very high, normally on very cold days, two pumps were turned on in order to be able to provide the necessary water to meet the demand. Therefore, due to this necessary pump rotation, for this case, data was gathered for two weeks, i.e., one week of information for each pump, for a period of approximately four months in the year of 2012 (February through May), equaling eight weeks of gathered data for this case.

Case 2:

For this case, the variable speed pumps were still running in discharge pressure mode in order to conform to the same type of work that the constant speed centrifugal speed pumps did in providing water to the system. However, in this case, both pumps were limited to providing water only to the deaerator tank. The valve allowing water to the heat exchanger was shut off. Then, after a certain amount of time, the heat exchanger was reopened in order to the compare the differences in flow rates and power consumption. Two different procedures were used to gather data for this case. However, the equipment, set up and software used to gather the data were the same as those described in Case 1.

The first procedure involved running both pumps on consecutive days with the heat exchanger access valve closed for a total of five hours, the time period considered to be the peak hours of demand of the power plant. The interval of data logging was still one minute for the information stored in the HOBO data loggers and as fast as the software could record when recording data from the variable speed pumps using the PC Tools E-Products software. This procedure was used for a total of one day for both pumps since it was established that, for the best comparison, the pumps should be run and compared based on the plant's demand for the same day and not consecutive days. This was due to the fact that, if the power plant's demand for those days were too different, that change would definitely influence the performance and power consumption of the two types of pumps.

For this reason, the second procedure involved starting the day with the constant speed pumps, running for two and a half hours with the heat exchanger access valve shut off, then swapping to the variable speed pumps running for another two and a half hours with the same setup. After this time, the access valve to the heat exchanger was opened, and the variable speed pumps were run in this setup for another hour. Once that hour elapsed, the constant speed pumps were run for another hour with the water flowing to the deaerator tank and the heat exchanger as well. Again, this was done so that the project could have information on how different or similar the pumps' performance would be on the same day when providing water to just the deaerator tank and then to both the deaerator tank and the heat exchanger. The data logging intervals used were the same as those described for the first procedure, and this method was used to gather data from the 15th through the 18th of April of 2013.

Case 3:

For this case, the Grundfos variable speed pumps were providing water to the system in level control mode. The variable speed pumps and the Worthington D-824 constant speed pumps were limited to providing water to the deaerator tank. The variable speed pumps were operated first and ran for a total of three hours in level control. The set-point chosen for the pumps to maintain was for the tank to be at 52% of its water capacity. As discussed previously in Section 2.2, with the variable speed pumps' controllers' normal settings, the pumps would slow down to their minimum performance, i.e., both pumps running at 40% speed, when the level set-point was met. And whenever the level would go below the desired 52%, the pumps would speed up, reaching their maximum performance after a short time to meet the desired set-point. Due to the lag that the controller has in speeding up and slowing down the pumps, the controller would not only overshoot the desired set-point, but also change the speed of the pump from minimum performance to maximum performance every time the deaerator level would drop as shown previously in Fig. 15 and Fig. 16.

For this reason, the Grundfos R100 programmer was used so that the range between the minimum and maximum performance of the pumps could be manually changed based on the demand for water that the deaerator tank required. In other words, so that the variable speed pumps did not keep constantly increasing and decreasing their speeds in order to maintain the desired set-point, the minimum and maximum performance settings were manually changed every few minutes until an optimum range was reached. This range allowed the minimum required power of the pumps to maintain the desired tank level for longer periods of time and only small increases and decreases in the pumps' speeds were necessary to bring the level back to the desired set-point once it varied. In order to be able to capture the data for any sudden changes in the flow rates of the variable speed pumps when running in level control mode, the data logging intervals of the HOBO data logger were changed to thirty seconds, and nothing was changed in the PC Tools E-Products software since it recorded any changes in the power consumption and discharge pressure as needed.

After running the variable speed pumps this way for about three hours, the work of supplying water to the deaerator tank was then taken over by the Worthington D-824 constant centrifugal pumps. Again, these pumps ran for three hours until the access valve to the heat exchanger was opened. Since these were constant speed pumps and no major changes in flow rates and power consumptions would occur as compared to those of the variable speed pumps, the data logging intervals of the HOBO data logger were one minute between each data point. Data gathering for this case was performed for a total of two days in April/May of 2013 (April 30th and May 1st).

Case 4:

For this case, the Grundfos variable speed pumps ran in level control mode and the Worthington D-824 constant speed pump operated in discharge pressure mode. Both pumps in this case were meant to supply water to the deaerator tank on the basement floor of the power plant and the heat exchanger on the first floor. However, due to the low discharge pressure that the Grundfos variable speed pumps produced when running in level control mode, only the Worthington D-824 constant speed pump was able to supply water to the heat exchanger.

When running the variable speed pumps in level control mode in this case, the same procedure explained in Case 3 was used. The only difference was that the pumps worked for a total of six hours in the day. After these six hours, the constant speed pumps took over the work for another six hours in order to obtain data about the same day for comparison of both pumps. The data logging interval of the HOBO data logger was still thirty seconds when obtaining data from the variable speed pumps and one minute when gathering data from the constant speed pumps. PC Tools E-Products was still used to log data about the power consumption and discharge pressure of the variable speed pumps. For this case, data was gathered in the manner described above for a total of eight days in March of 2013 (11, 12, 14, 18, 19, 20, 21, and 26) and two days in April of 2013 (1 and 2).

2.4 Life Cycle Costs and Equations

The life cycle cost analyses for each of the four cases considered in this project were created using the Building Life Cycle Cost Software provided by the U.S. Department of Energy [23]. This section is dedicated to showing all of the costs that were taken under consideration for both pump systems and the equations that the software used to calculate the present value for each cost, employing a study period of twenty years. All four cases followed the same procedure. The only difference was the energy consumption that was estimated based on the results of the data gathered from both pump systems during each case's runs.

For a life cycle analysis, there are two dates needed to start the analysis, the Base date and the Service date. Base date is the time when all project-related costs, i.e., investment and installation costs, are applied to the life cycle cost analysis, which is usually the first day of the study period of the project. The service date is the date that the project is expected to be implemented, i.e., the date which the pumps started running, such that energy and water costs only start at this date [25]. The base date of this project was considered to be same as the service date of the project which started on August 1st of 2012.

Following the Federal Energy Management Program rules for life cycle cost analysis, all annually recurring costs were discounted from the end of the year at rates of 3.0% real discount (interest rates not including inflation) and 3.5% nominal discounts (interest rate that includes inflation) provided by the Department of Energy (DOE). In other words, these discount rates were the rates used to transform the future values of the annually recurring costs into present value costs. Also, the analysis information is based on Current Dollar Analysis, which includes general inflation of 0.5% for current dollar amounts, nominal discount (interest rate that includes inflation) and escalation rates (the rate of change over time of a value such as energy costs) [23].

Table 1 shows the formulas that the software used to calculate the present values of all costs used to calculate the total life cycle costs for both pump systems considered in this project as well as a visual representation of what each formula is trying to achieve [25]. For both pump systems, the energy and water costs were determined by contacting local energy companies, i.e., Westar Energy, and the City of Lawrence water service, respectively. Since the power plant follows an industrial rate schedule, it was determined that Westar charges US$0.079 per kWh and a US$480.00 Annual Demand Charge. The City of Lawrence charges the University of Kansas'

Power Plant US$0.00287 per gallon of water consumed as shown in the city's industrial billing rates table [30, 31]. This document assumes that the power plant has no water disposal costs as stipulated by the City of Lawrence. The energy cost is represented by the variable "**E**" in Eq. (2), and the present value of this cost is calculated by the BLCC software using the fourth formula in Table 1. The water cost is represented by the variable "**W**" in Eq. (2), and its present value is calculated by the software using the third formula in Table 1.

The next values to be input in the software were the initial investment costs for each pump system. The initial investment costs were calculated as one time occurring amounts, and are represented by the variable "**I**" in Eq. (2), for which the present value cost for the twenty years study period is calculated by the BLCC software using the first formula shown in Table 1. For the Worthington D-824 constant speed centrifugal pump, the cost of the pump and the control valve were considered to be investment costs, since the pump is not able to provide water to the system without having the control valve to control the flow of water. The pump cost was determined to be US$2,500.00 and the Fisher control valve to be US$4,000.00 [26, 32]. The Grundfos variable speed pump system installed at the power plant was determined to have an initial investment cost of US$15,000.00, which included both pumps and the CR Monitoring controller [33]. It was assumed that both pump systems will have no residual value at the end of the study period of twenty years.

The next set of costs included replacement costs such as seals (US$200.00 for both pumps) that are normally replaced every two years, and replacement of motors or impellers (US$1000.00 for Worthington D-824 and US$2000.00 for CRE 15-3) changed as necessary, but averaged to be replaced every ten years from the pump's installation date for the sake of this project. The seals and motor and impellers were considered to be "one-time amounts" in the software (since they are costs that occur one time every two years for the seals and every ten years for the motor/impellers). These costs are represented by the variable "**Repl**" in Eq. (2), and their present values (for every time they occur) are calculated by the BLCC software using the first formula in Table 1 since the formula takes in account the year of the study period that the cost occurs. All operating (down time), and maintenance (e.g., labor necessary to change seals/impellers) were considered under the cost of labor, which was assumed to be an "annually recurring cost" with a labor cost value of US$1,000 being used for both pumps every year. The labor costs are represented by the variable "**OM&R**" in Eq. (2), and its present value is calculated by the BLCC software using the second formula presented in Table 1 [25].

All of the formulas shown in Table 1 use inflation, price escalation rates, and discount rates determined by DOE. These rates are uploaded into the software and updated at the end of every federal fiscal year, which ends September 30th. To obtain the updated software, one simply has to register and download it from the DOE website for free. Tables Ba-1 through Ba-5 cited in Table 1 can be found in Reference 25.

Once the software calculates every individual cost using the formulas shown in Table 1, it uses the following simple equation to determine the total present-value life cycle cost for the two pump system alternatives discussed in this document:

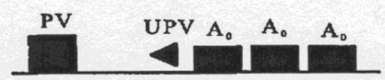
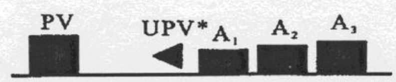
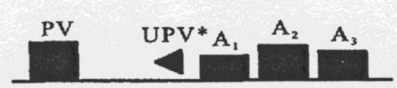
$$\mathbf{LCC = I + Repl - Res + E + W + OM\&R} \qquad (2)$$

(Terms are defined in the Nomenclature)

A life cycle cost analysis was performed for each of the four cases discussed in this document (see Section 2.3), where the only costs that were changed in the software from case to case was the energy consumption of each pump for each case and the water usage in the 12 month period being discussed in each case, since energy costs/savings and water usage are the highest costs the power plant has and were the primary focus of this project. The annual energy consumption given in kilowatt hours for each case was estimated based on the power consumption data gathered in kilowatts for each case. Most of the data obtained was during the months that the power plant had its highest demand due to the cold weather and the amount of buildings requiring steam, i.e., winter. The estimates of energy consumption made for the months in which data was not gathered were based on these coldest months in order to obtain the power plant's annual energy consumption. Tables of the outside temperatures and the steam produced by the power plant for when the data was taken are shown in Appendices D and E, respectively.

Table 1: Present-Value Formulas and Discount Factors for Life Cycle Cost Analysis [Reproduced from Ref. 25]

Present-Value Formulas and Discount Factors for Life-Cycle Cost Analysis.

PV formula for one-time amounts The **Single Present Value (SPV) factor** is used to calculate the present value, PV, of a future cash amount occurring at the end of year t, F_t, given a discount rate, d. $PV = F_t \times \frac{1}{(1+d)^t}$	$PV = F_t \times SPV_{(t,d)}$  The **SPV factor** for d = 3% and t = 15 years is **0.642**.
PV formula for annually recurring uniform amounts The **Uniform Present Value (UPV) factor** is used to calculate the PV of a series of equal cash amounts, A_0, that recur annually over a period of n years, given **d**. $PV = A_0 \times \sum_{t=1}^{n} \frac{1}{(1+d)^t} = A_0 \times \frac{(1+d)^n - 1}{d(1+d)^n}$	$PV = A_0 \times UPV_{(n,d)}$  The **UPV factor** for d = 3% and n = 15 years is **11.94**.
PV formula for annually recurring non-uniform amounts $PV = A_0 \times \sum_{t=1}^{n} \left(\frac{1+e}{1+d}\right)^t = A_0 \frac{(1+e)}{(d-e)}\left[1 - \left(\frac{1+e}{1+d}\right)^n\right]$ The **Modified Uniform Present Value (UPV*) factor** is used to calculate the PV recurring annual amounts that change from year to year at a **constant** escalation rate, e (i.e., $A_{t+1} = A_t \times (1+e)$), over n years, given d. The escalation rate can be positive or negative.	$PV = A_0 \times UPV^*_{(n,d,e)}$  The **UPV* factor** for e = 2%, d = 3%, and n = 15 years is **13.89**.
PV formula for annually recurring energy costs (FEMP LCCA) The **FEMP UPV* factor** is used to calculate the PV of annually recurring energy costs over n years, which are assumed to change from year to year at a **non-constant** escalation rate, based on DOE projections. FEMP UPV* factors are precalculated for the current DOE discount rate and published in tables Ba-1 through Ba-5 of the Annual Supplement to Handbook 135.	$PV = A_0 \times UPV^*_{(reg,\ ft,\ rt,\ d,n)}$  The **FEMP UPV* factor** for region (reg) = 3, fuel type (ft) = electricity, rate type (rt) = commercial, d = 3%, and n = 15 is **12.12** (1995).

In order to have a better estimate of the annual energy demand of the power plant, estimates were made for every month of the year based on the information gathered from Cases 1 through 4. Since the monthly energy consumption is directly related to the monthly steam production, energy estimates for the months in which information was not gathered were estimated based on the comparison of those months' steam production to the steam production of the months from which data was obtained. For example, the energy consumption of March was calculated based on the data collected for certain days of that month, i.e., power consumption data. If one wanted to estimate the energy consumption of the plant during the month of July, for which just the total steam produced by the plant during that month is known, the energy consumption of March could be multiplied by the ratio of the total steam produced in July and the total steam produced in March in order to have an estimate of the energy consumption of July based on steam production. Therefore, this was the approach used for all four cases in this project in order to have a better estimate of the annual energy consumption of the Power Plant, since summer months are expected to have a much lower steam demand than winter months. See Appendices F through J for the power and energy consumption hand calculations made to obtain the annual energy consumption for Cases 1 through 4.

2.5 Data Logging Error Analysis

Since multiple sensors of different models were used to measure all of the necessary data in this project, it is important to provide their ranges of accuracy in order to properly evaluate the quality of the results. For this reason, an error analysis for each piece of equipment used in this project follows.

2.5.1 Data Logger

The data loggers used in this project were HOBO U12-006 Data Loggers. They have an accuracy level of ±2.5% of the reading being received from each individual sensor used to acquire data from both pump systems, i.e., pressure, flow rate and power consumption [27]. (Specifications for all equipment can be found in Appendix C). The CU351 controller of the Grundfos variable speed pumps was used to receive the analog input from the level transmitter when the pumps ran in level control mode. This controller has an accuracy of ±0.5% of the full scale reading of the input [34]. Since the data loggers and the sensors have their own levels of accuracy, this thesis will be using Eq. (3) in order to determine the total error of the readings acquired by the sensors and data stored in the data loggers [35]:

$$u_I = \sqrt{\sum_{i=1}^{N} e_i^2} \qquad (3)$$

(Terms are defined in the Nomenclature)

2.5.2 Flow Meters

When dealing with the Siemens magnetic flow meter 3100 and its controller, Siemens Sitrans Mag 5000, the company provides a flow sizing program that allows the user to determine the accuracy of the flow meter, given the pipe diameter in which the sensor was installed as well as the minimum and maximum flow rates for the application. For every flow rate, the sensor has a different level of accuracy, where the greater the flow rate the lower the error. The flow meters installed on the discharge side of the constant speed pump and the variable speed pumps were both four inch diameter magnetic sensors. By analyzing the data obtained from them, it was established that the minimum flow rate was never lower than 40 GPM and that the maximum flow rate never exceeded 300 GPM. Therefore, these were the values used in the program to establish the accuracy levels of these two sensors. Table 2 shows the different maximum error values of these sensors for different flow rates based on minimum and maximum flow rates of 40 GPM and 300 GPM:

Table 2: Level of Accuracy of Siemens Magnetic Flow meter MAG3100 with a Four Inch Diameter Sensor [Reproduced from Ref. 36]

Calculations on MAG3100 DN 100 / 4" sensor

SIEMENS

Back Print table

Selected flow range

Flowrate [Gal(US)/min]	Flow velocity [ft/s]	Max. error *) [% of Flowrate]
40	1.05	± 0.71
83	2.20	± 0.55
127	3.34	± 0.50
170	4.48	± 0.47
213	5.62	± 0.46
257	6.76	± 0.45
300	7.91	± 0.44

Low flow range

Flowrate [Gal(US)/min]	Flow velocity [ft/s]	Max. error *) [% of Flowrate]
12	0.33	± 1.40
21	0.55	± 1.00
124	3.28	± 0.50

Maximum flow rate

Flowrate [Gal(US)/min]	Flow velocity [ft/s]	Max. error *) [% of Flowrate]
1,245	32.81	± 0.41

Select flowrate function: Focus on the whole flow range (Linear)

Accuracy: 0.4% ± 1.0 mm/s

The following data are used for the calculation:

Transmitter choice:	MAG5000
Sensor choice:	MAG3100
Minimum flow rate:	40 Gal(US)/min
Maximum flow rate:	300 Gal(US)/min

By using Eq. (3) to combine the error of the data logger (±2.5% of the reading) with the error for the minimum and maximum flow rates shown on Table 2, the range of the total error that could be encountered when reading the data recorded by the HOBO data loggers would be ±2.599% for 40 GPM to ±2.538% for 300 GPM.

The same program was used to determine the range of error from the flow meter using the one inch diameter sensor installed in the bypass marked in purple on the power plant schematic (Fig. 9). Again, by analyzing the data acquired by this flow meter, it was determined that the lowest possible flow rate recorded by it was 1 GPM with the maximum being 20 GPM, just so that a range of error could be calculated for this flow meter. Using these values, Table 3 shows the range of errors for the Siemens flow meter that used a one inch diameter sensor.

Table 3: Level of Accuracy of Siemens Magnetic Flow meter MAG3100 with a One Inch Diameter Sensor [Reproduced from Ref. 36]

Calculations on MAG3100 DN 25 / 1" sensor

SIEMENS

Back Print table

Selected flow range

Flowrate [Gal(US)/min]	Flow velocity [ft/s]	Max. error *) [% of Flowrate]
1.00	0.42	± 1.18
4.17	1.76	± 0.59
7.33	3.09	± 0.51
10.50	4.43	± 0.47
13.67	5.76	± 0.46
16.83	7.10	± 0.45
20.00	8.43	± 0.44

Low flow range

Flowrate [Gal(US)/min]	Flow velocity [ft/s]	Max. error *) [% of Flowrate]
0.78	0.33	± 1.40
1.30	0.55	± 1.00
7.78	3.28	± 0.50

Maximum flow rate

Flowrate [Gal(US)/min]	Flow velocity [ft/s]	Max. error *) [% of Flowrate]
77.81	32.81	± 0.41

Select flowrate function: Focus on the whole flow range (Linear)

Accuracy: 0.4% ± 1.0 mm/s

The following data are used for the calculation:

Transmitter choice:	MAG5000
Sensor choice:	MAG3100
Minimum flow rate:	1 Gal(US)/min
Maximum flow rate:	20 Gal(US)/min

When taking in consideration the reading accuracy of the HOBO data logger (±2.5%), the range of the total error for the data taking using the one inch diameter flow meter is between ±2.764% for 1 GPM to ±2.538% for 20 GPM.

2.5.3 Pressure Transducers

All pressure transducers used to gather data for this project were made by Danfoss for industrial applications (type MBS 3000). They were used to measure the discharge pressure and the pressure on the suction sides of the Worthington D-824 constant speed centrifugal pump and the Grundfos CRE 15-3 variable speed pumps. One of these sensors was also used to measure the pressure right before the control valve located at the deaerator tank. The measurement range of these transducers was from 0 to 4 bar. According to the technical data (see Appendix C), the transmitter's accuracy, which includes non-linearity, hysteresis, and repeatability, is typically ±0.5% of full scale reading, but having a maximum error of no more than ±1% of full scale reading. For this reason, it was assumed that these transducers have an accuracy of ±1% of full scale reading. This means that for every pressure data point acquired by these transducers, the error was considered to be ±0.04 bar [37]. The data logger accuracy must also be taken in consideration for the data obtained from the pressure transmitter. So a range of accuracy must be established from the lowest values recorded to the maximum reading of the transmitter, since the error of the transmitter is based on the full scale reading and the data logger error is a fixed percentage of every reading received from the transmitter. Considering that the lowest value ever recorded by these transducers in this project was 0.1 bar and the maximum reading was 4 bar, the total error of the recorded values of the data logger and the pressure transmitter was between ±40.078% (at 0.1 bar) and ±2.693% (at 4 bar). Since most of the data that was recorded by these transducers were not lower than 0.8 bar, the range of error for the great majority (over 90%) of recorded values from these transducers was between ±5.59% (0.8 bar) and ±2.693% of reading.

2.5.4 Differential Pressure Sensor

In order to obtain and record the pressure drop that the Fisher control valve created before the water went into the deaerator tank, Grundfos provided a differential pressure sensor for industrial applications (type DPI 0-2.5). As the model number indicates, the range of differential pressure that this sensor read was from 0 to 2.5 bar. The accuracy of its readings was ±2% of its full scale. Again, this means that for every differential pressure measurement gathered from this sensor, the error was ±0.05 bar [38]. Assuming that the lowest recorded value by this differential pressure transducer was 0.1 bar, our range of error between the lowest recorded value and maximum possible reading of the sensor was between ±50.063% (0.1 bar) and ±3.20% (2.5 bar) of the actual recorded value. The low pressure error is high because the sensor’s accuracy is based on full scale. Most of the data recorded by this sensor (over 90%) was above 1 bar since it was mainly used when the control valve next to the deaerator tank was in use. Thus, most of the values recorded by this sensor and used in this project had errors between ±5.59% and ±3.20% of the actual reading.

2.5.5 Power Monitoring Transducer

The energy consumption of the Worthington D-824 constant centrifugal pump was recorded using Veris Power Monitoring H8044-0100-2 current transducers. The current transducers’ information was used by a computer attached to the sensors and to the voltage supply of the pumps which then calculated the power consumption. The accuracy of the calculated power consumption was given as ±1% of the reading from 10% to 100% of the rated current of the current transducers (see Appendix C). Since these transducers were rated at a maximum amperage of 100 amperes, as long as the current going through the power cables of the pumps was between 10 and 100 amps, the accuracy of the calculated power consumption values would be within ±1% of the actual reading [39]. Since the amperage did not go below 10 amps or above 100 amps when the pump was in service, the data gathered in this project was within this 1% error. In this case, since both the sensor and the data logger have an established accuracy for the actual reading, the combined error for this sensor and the HOBO data logger was ±2.693% of each value recorded.

The Grundfos variable speed pumps system controller is capable of displaying and recording the instantaneous power consumption of the pumps. However, Grundfos was unable to provide the accuracy of the controller for its measurements. For this reason, the power accuracy levels for these pumps were unknown. However, based on the accuracy of similar devices, a conservative estimate would place these measurements at ±5% or less of reading.

2.5.6 SureSite® Level Transducer

The SureSite® level transmitter's accuracy is ±0.4% of its full scale, while the Grundfos CU351 controller has an accuracy of ±0.5% of the full scale of its analog input [29, 34]. Using Eq. (3), this gives a total error of ±0.640% of the full scale of the transmitter. Since the maximum height of water that the transmitter measured was 37.5 inches, for every level measurement that the controller of the variable speed pumps receives, the error in the height of the water was within ±0.24 inches. The lowest level measured was approximately 18 inches (read as 48% level by the pumps' controller), and since both the pumps and the transmitter had an accuracy based on the signal's full scale, the error for such reading was still ±0.640% or ±0.24 inches.

2.5.7 Error Analysis Summary

Having established the error analysis for each sensor and data logger used in this project, this information should be taken into consideration for the analyses of the results from this project. Representative errors will be plotted with some of the data presented in order to provide a visual representation of the data's accuracy in this section so that readers take such errors under consideration when looking at the data presented in the results. (More detailed specifications for all instrumentation used in this project are available in Appendix C.)

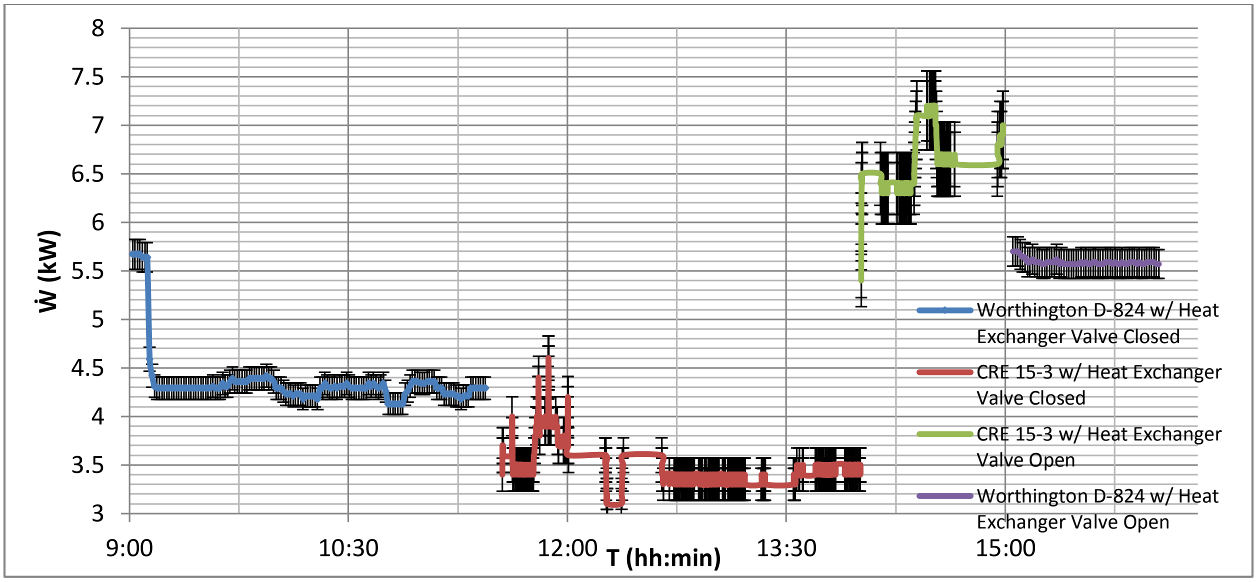


Figure 19: Representative Error Bars for Power Consumption Readings (April 18, 2013).

Figure 19 shows the errors that should be taken into consideration for the power consumption results obtained for the Worthington D-824 pump (±2.693% of reading) and the Grundfos CRE 15-3 pumps (±5% of reading, assumed error).

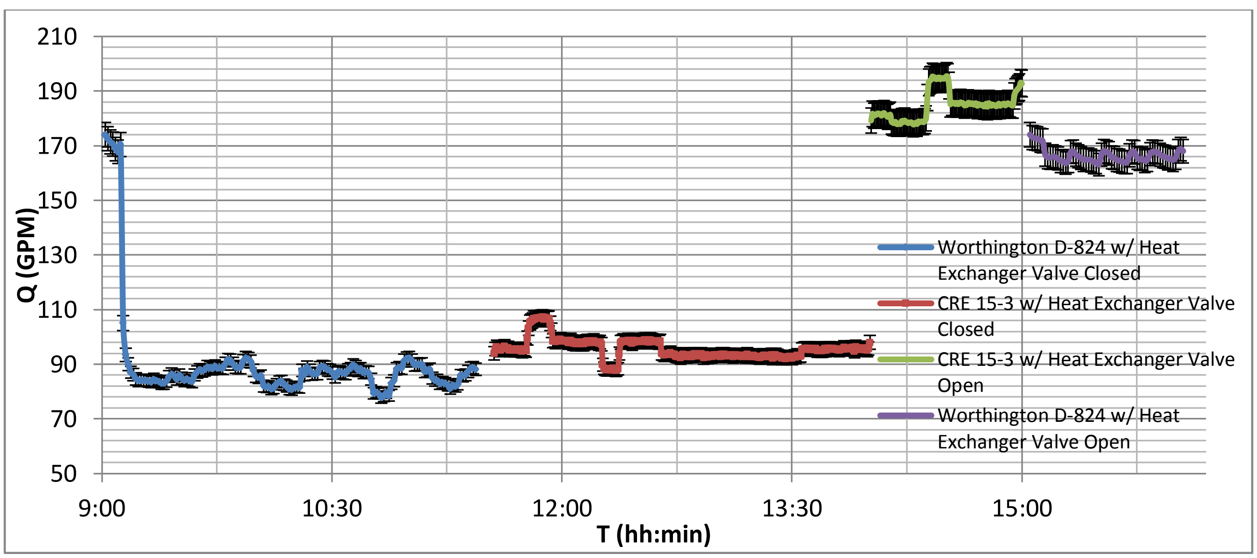


Figure 20: Representative Error Bars for Flow Rate Readings (April 18, 2013).

The expected errors for the flow rate readings in this project are presented in Fig. 20, where the average error was approximately ±2.50% of every value obtained for the discharge flow rate of both pumps systems.

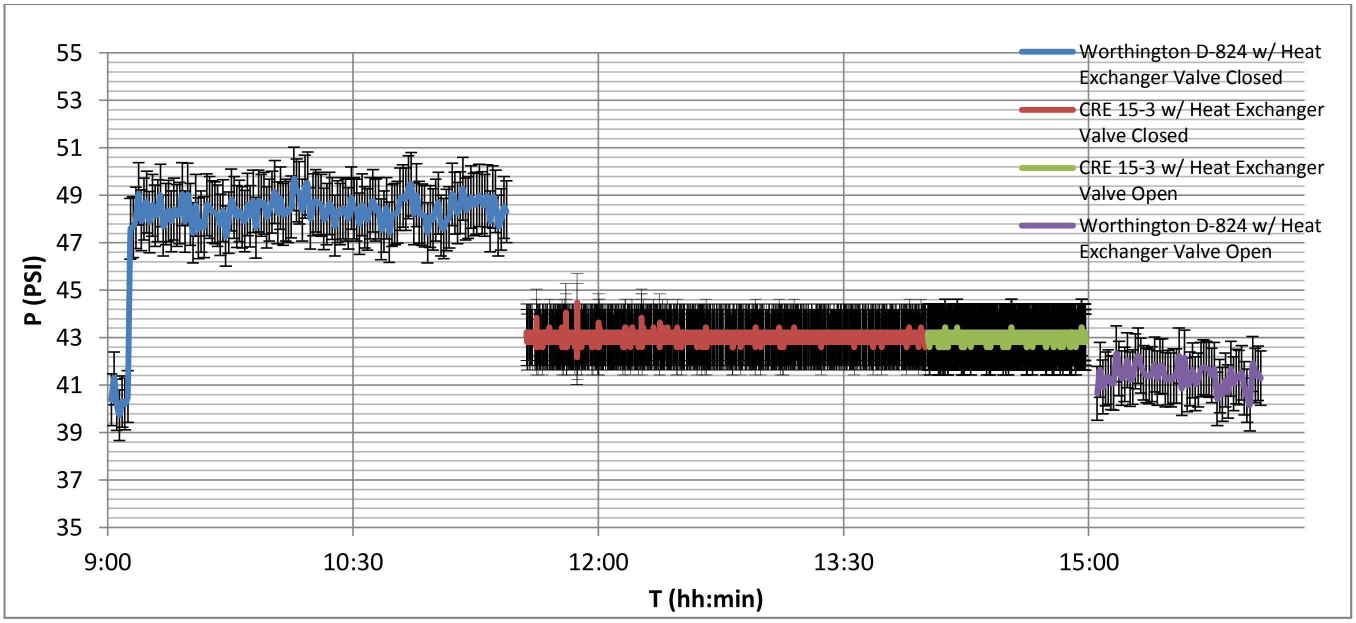


Figure 21: Representative Error Bars for High Discharge Pressure Readings (April 18, 2013).

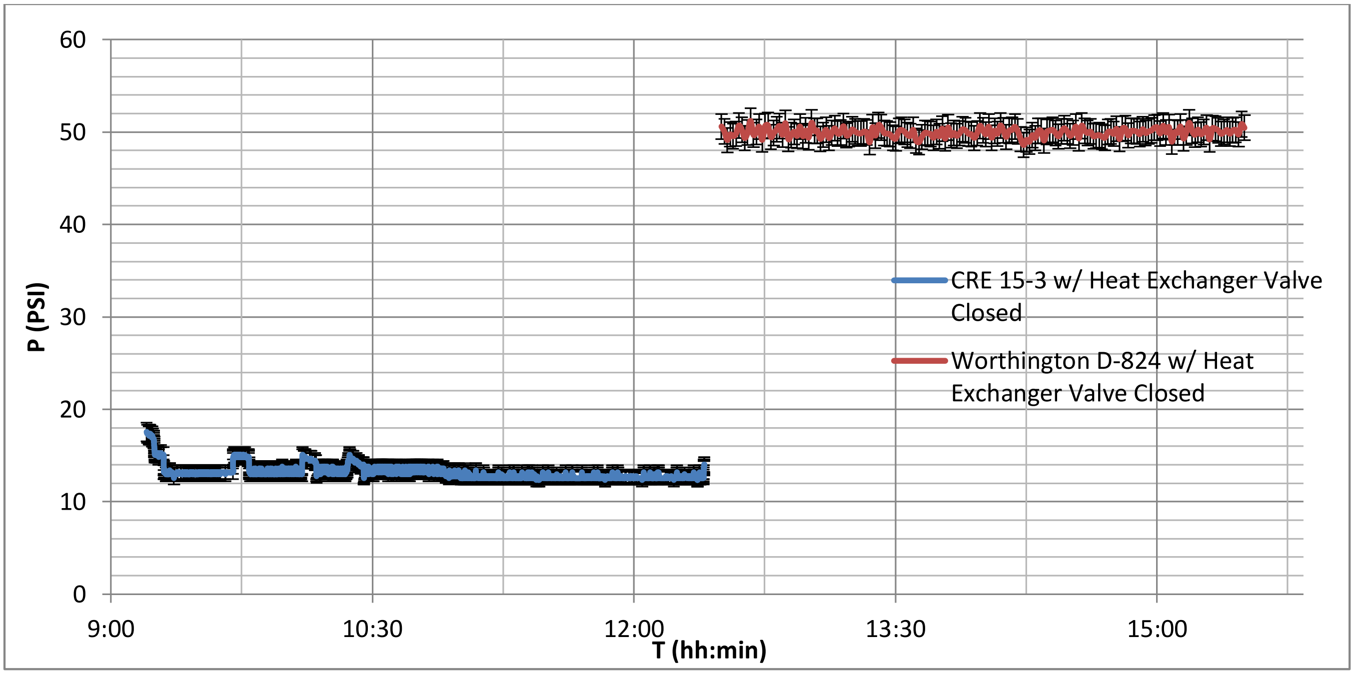


Figure 22: Representative Error Bars for Low and High Discharge Pressure Readings (May 1, 2013).

Examples of the representative errors for high and low discharge pressures are shown in Figs. 21 and 22. The average error for the higher discharge pressure readings, i.e., above 40 PSI, was approximately ±2.75% of reading, while, for the lower discharge pressure readings, the error was approximately ±5.7% of the value recorded by the data logger.

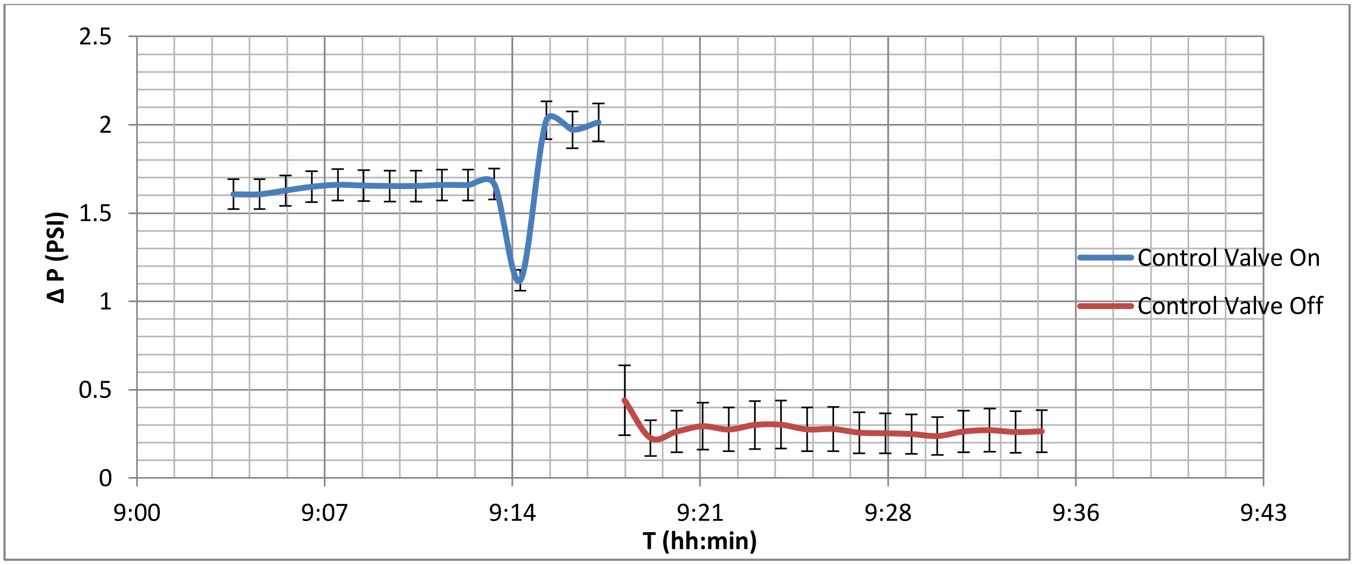


Figure 23: Representative Error Bars for High and Low Differential Pressure Readings across Control Valve (March 12, 2013).

Figure 23 shows the representative error for the values obtained for the differential pressure across the control valve when the valve was "on" and "off", i.e., "on" meaning in use when running the constant speed pumps and variable speed pumps in discharge pressure mode, and "off" meaning fully open when running the variable speed pumps in level control mode. The error of the values recorded while the control valve was on was approximately ±5.3% of reading, while the error for the values recorded while the valve was off was approximately ±45% of reading.

All errors presented in this section should be taken into consideration when reading the results of this document, since these representative errors will not be presented on the graphs in the results section.

Chapter 3: Results

3.1 Case 1

3.1.1 February 11 through February 23, 2012

The following graphs show a comparison between the Worthington D-824 constant speed pump and the Grundfos CRE 15-3 variable speed pumps' power consumption, flow rates and discharge pressures while both were running in discharge pressure mode from February 11 (Saturday) through February 23 (Thursday) of 2012.

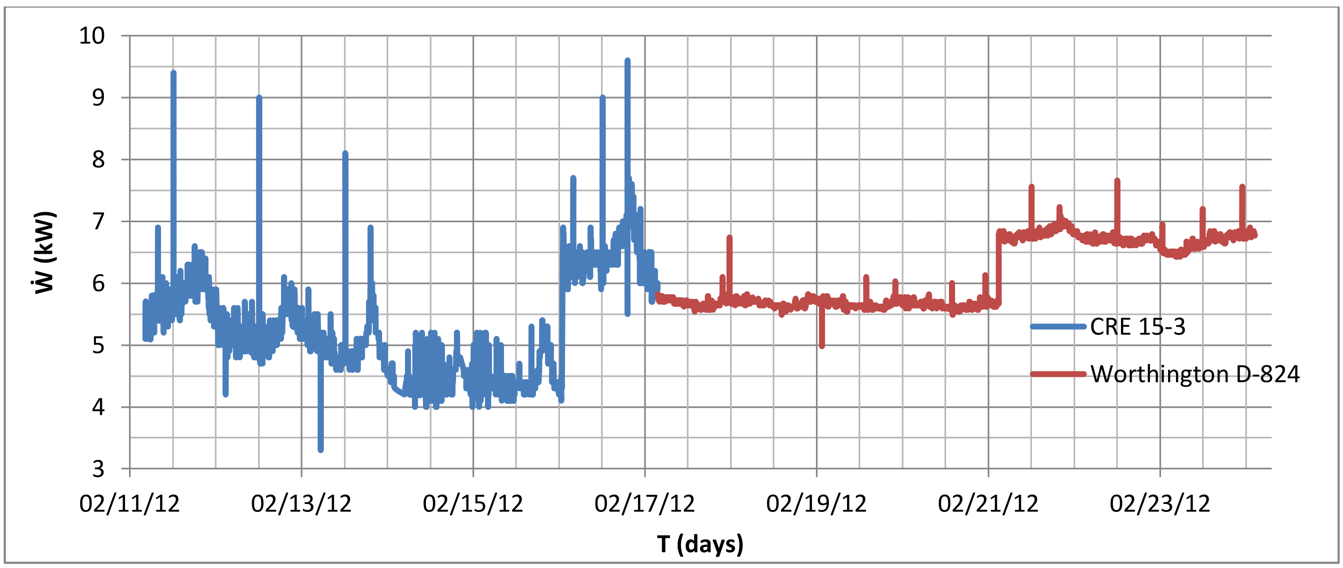


Figure 24: Grundfos CRE 15-3 vs. Worthington D-824 Power Consumption for February 11- 23, 2012

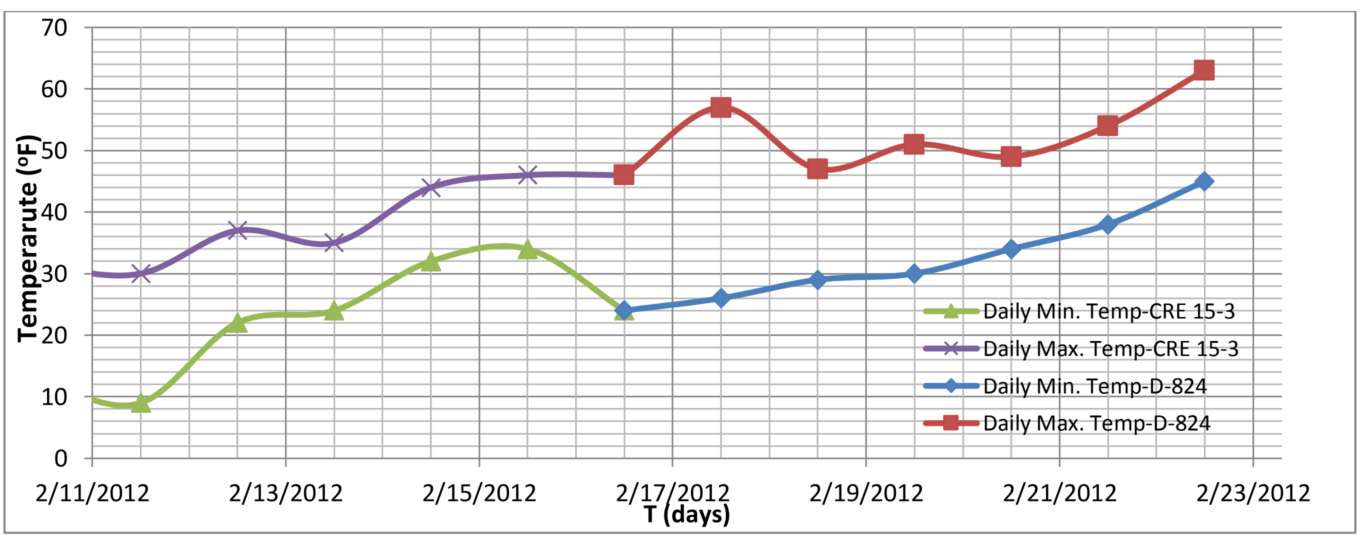


Figure 24a: Daily Maximum and Minimum Ambient Temperatures for February 11-23, 2012

Figure 24 shows a comparison of the power consumption between the Grundfos CRE 15-3 variable speed pumps running in discharge pressure mode and Worthington D-824 constant speed pump. The variable speed pumps ran from February 11 through February 17 while the constant speed pump ran from February 17 through February 23. The average power consumption of the Grundfos pumps was 5.280 kW while the average power consumption of the Worthington D-824 pump was 6.117 kW. As Fig. 24 shows, the power consumption for the Worthington D-824 pump was higher from February 21 through February 23, which caused the average power consumption to be higher as well. This was due to the power plant requiring a higher steam demand as the flow rates shown in Fig. 25 also demonstrate. The same increase in steam demand can be seen when running the Grundfos CRE 15-3 from February 16 through February 17. However, since that period of time was smaller than the period for the Worthington D-824, the average power consumption was not affected as much.

Figure 24a shows the maximum and minimum outside temperatures for the days that the pump systems operated [45]. Based on the fact that one of the power plant's jobs is to provide steam for the heating system of the campus, lower outside temperatures can cause the power plant's demand for water to become higher. In other words, the flow rates and power consumption of the pumps would be higher, the lower the outside temperate was. The fluctuations of power based on temperature changes are a lot more noticeable during the days in which the Grundfos CRE 15-3 pumps were running. That is because of the increase and decrease of their speeds in order to satisfy the demand for water that the power plant required. Since the Worthington D-824 pump is a constant speed pump, its power consumption changes were minimal when compared to those of the Grundfos CRE 15-3 pumps. There reason for that is that the control valve is doing all the work of increasing and decreasing the demand of water to the deaerator tank. Figure 24a shows an increase in temperature for the period of February 21 through February 23, which should indicate a decrease in power consumption for the Worthington D-824. However, Fig. 24 shows a slight increase in power during that time frame. The reader should also keep in mind the fact that the power plant has other duties that could require higher steam production other than just heat supply, e.g., supply steam for humidity in HVAC systems around campus.

In later sections, these average power consumption results will be compared to the pump curves and to hydraulic power calculations (using the average flow rates and discharge pressures from each pump system) in order to ensure that the obtained values for both pump systems are reasonable, i.e., fit the physics of flow, so that a fair comparison can be made.

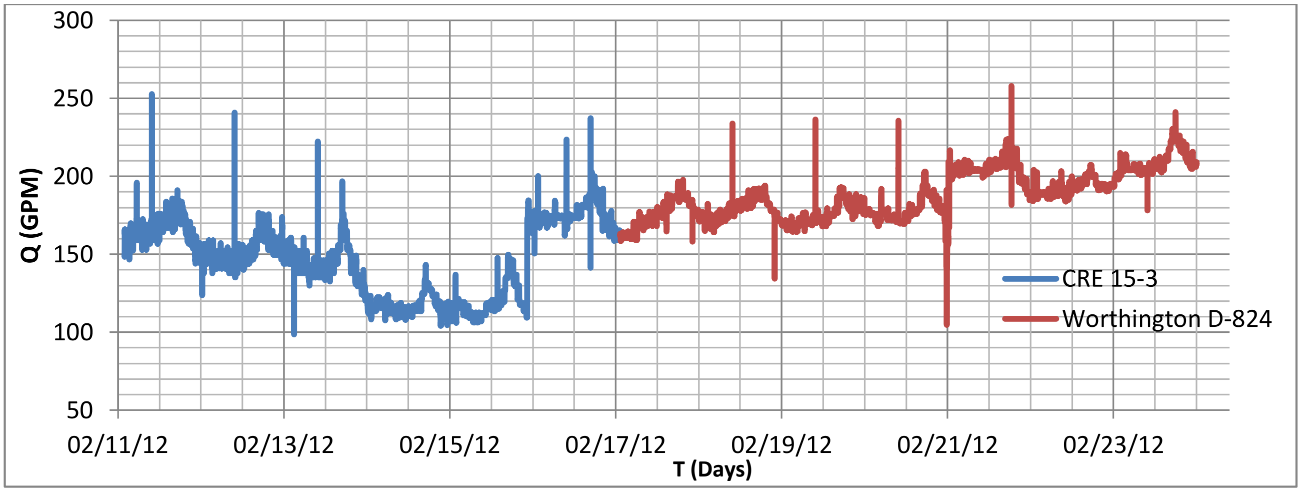


Figure 25: Grundfos CRE 15-3 vs. Worthington D-824 Flow Rate for February 11- 23, 2012

The average flow rate of the CRE 15-3 pumps from February 11 through February 17 was 145.86 GPM and the average flow rate of the Worthington D-824 pumps from February 15 through February 24 was 187.80 GPM. These values show how the demand was higher during the week in which the Worthington D-824 pump was running, explaining the higher power consumption mentioned previously.

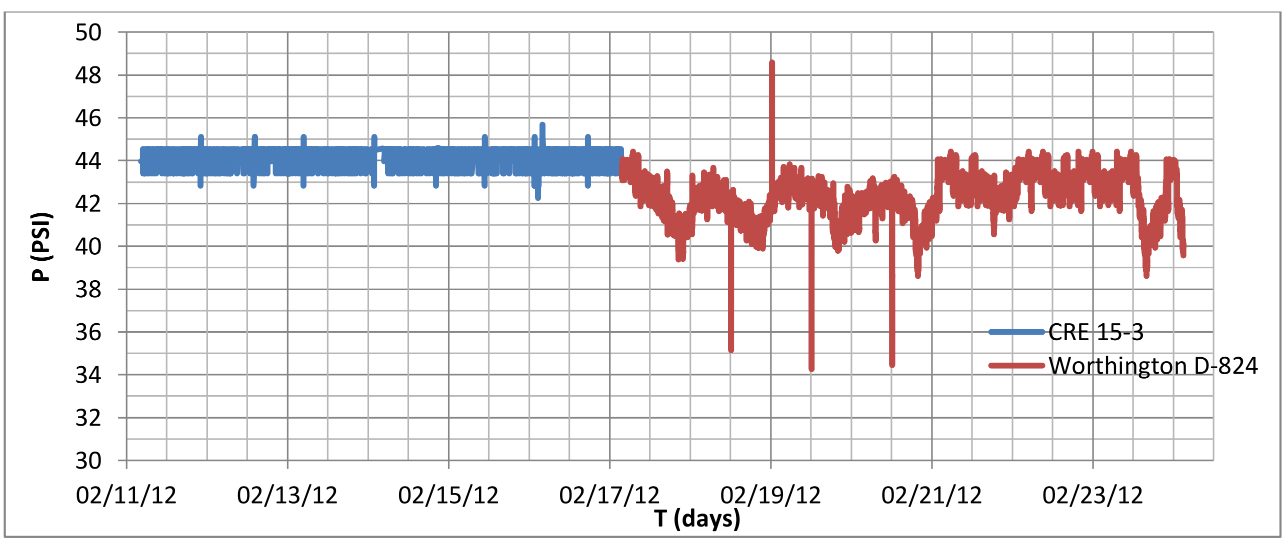


Figure 26: Grundfos CRE 15-3 vs. Worthington D-824 Discharge Pressure for February 11- 23, 2012

As Fig. 26 shows, the discharge pressure of the CRE 15-3 pumps did not fluctuate as much when compared to the discharge pressure of the Worthington D-824 pump. That is because, when running the CRE 15-3 in discharge pressure mode, a set point had to be chosen, which was 44 PSI. This means that the pumps tried to maintain a discharge pressure of 44 PSI at all times as guided by their controller, while the Worthington D-824's discharge pressure was mainly influenced by the control valve regulating the flow of water into the deaerator tank. The average discharge pressures for the CRE 15-3 pumps and the Worthington D-824 pump were 44.06 PSI and 42.33 PSI, respectively.

The pump curves of both pump systems are available in Appendix B (Note that "P" in Appendix B for Pump Curves is Power and not Pressure). It should be noted that the pump curves for both pump systems provide their pressure information as head in feet. Since the information gathered in this project used PSI as the unit of pressure, Equation (4) [40], was used to convert the known pressure in PSI to head in order to use the pump curves' information.

$$\boldsymbol{H} = \frac{P \times 2.31}{SG} \tag{4}$$

(Terms are defined in the Nomenclature, SG for this project is equal to 0.979 due to the water's average temperature of 160°F [40])

When using the Grundfos' pump curves that are provided on their website (WEBCAPS) [41], this version allows the user to manually input values for flow rate and discharge pressure [41]. Once these values are entered, the power consumption of the pump as well as its efficiency are automatically calculated and displayed to the user. That is why the values obtained from the pump curves for the CRE 15-3 pumps have more significant figures than the values found for the Worthington D-824 pump.

When applying the average flow rate and discharge pressure data to the CRE 15-3 pump curve, the power consumption of the pump was approximately 4.9 kW, being close to the recorded value of 5.28 kW, the difference between the curve value and the measured value was approximately 7.2%. The value used is referenced in the pump curve as P1, which is the power input that the consumer has to pay for (refer to Appendix B.2 horsepower curves) [33]. (Note that this is not the "pressure" as is found in the nomenclature, since P1 in the curve represents horsepower.) By following the same procedure with the Worthington D-824 pump, the power consumption of the pump using the curve values was approximately 7.6 HP, which is equivalent to 5.67 kW. The average power consumption from the recorded data was 6.117 kW which gives approximately 7.31% difference between the two values. Therefore, since the recorded power consumption results have small differences when compared to the pump curve values, it is reasonable to say that the data gathered in this document is consistent with the pump curves for both pump systems.

Another way to check that the power consumption data is consistent with the flow rate and discharge pressure information is by calculating the hydraulic power of the pump in HP using Eq. (5) [42] (See Appendix F for the derivation of Eq. (5).)

$$\dot{W}(\mathbf{HP}) = \frac{Q(GPM) \times P(PSI)}{1714.29 \times \eta} \qquad \textbf{(5)}$$

(Terms are defined in the Nomenclature)

Normally, the pressure used in Eq. (5) is the differential pressure between the pump's discharge pressure and the pump's inlet pressure. However, since the inlet pressure for both pump systems in this project was so low, i.e., an average inlet pressure of 1 PSI, the average discharge pressure was used in Eq. (5). By entering the average flow rate and discharge pressure values of the CRE 15-3 pump system in its pump curve "software", it showed that the pumps have an efficiency of approximately 72%. When using all of these values in Eq. (5), the hydraulic power of the pump was 5.206 HP, which is 3.88 kW. This power consumption is about 26.5% less than what was obtained using the recorded values. However, according to Grundfos, in order to obtain the true power consumption of the pumping system, one must use the efficiency of the pump and the motor combined (the WEBCAPS pump curve provides a efficiency only considering the pump as well as a combined efficiency of the pump and motor) [41]. The pump curve shows this efficiency to be 58.7%. When using the pump and motor combined efficiency (58.7%), the hydraulic power of the pump was 6.376 HP, or 4.754 kW. This value is 9.96% higher than the value obtained through data gathering, which is closer than the value obtained when just using the pump efficiency. Therefore, these values not only show that the data gathered for the power consumption is fairly close to the two types of calculated power consumption, but also that the combined pump and motor efficiency must be used when calculating the pumping system's hydraulic power. Since the comparison of the recorded power consumption values to the pump curve power consumption values (given the flow rate and discharge pressure) was close, it is assumed that the calculated hydraulic power is different due to the efficiency of the pump not being as high as expected. Thus, it is assumed that the pumps were running at a lower efficiency, so that the calculated power consumption would be closer to the power consumption value recorded.

When using Eq. (5) to calculate the power consumption of the Worthington D-824 pump (using an estimated pump efficiency of 69% obtained from the pump curve in Appendix B.1), the power obtained is 6.72 HP which is equivalent to 5.01 kW. This value is about 18.1% lower than the recorded value. Again, this could be due to the fact that the curve is only considering the pump efficiency and not the combined pump and motor efficiency. Since the Worthington D-824 pump curve does not provide a combined efficiency like the Grundfos pump curve, it must be estimated through calculations. This new efficiency value can be obtained by multiplying the ratio of the calculated power consumption (5.01 kW) and the recorded power consumption (6.117 kW) by the efficiency found in the pump curve (69%). By using this process, in order to have the calculated power equal to the recorded power consumption value, the pump and motor combined efficiency should be 56.51%. This value is lower than the one found in the pump curve, however, the CRE 15-3 efficiency also dramatically dropped (from 72% to 58.7%) when the pump and motor efficiencies were combined. Hence, this calculation could be considered a fair estimate for what the Worthington D-824 combined pump and motor efficiency should be.

These two different approaches, which were used to verify how close the power consumption obtained via data gathering was when compared to the values obtained from the pumps' performances (flow, discharge pressure and efficiency) and their pump curves, will be employed in all of the results included in Chapter 3.

3.1.2 March 1 through March 14, 2012

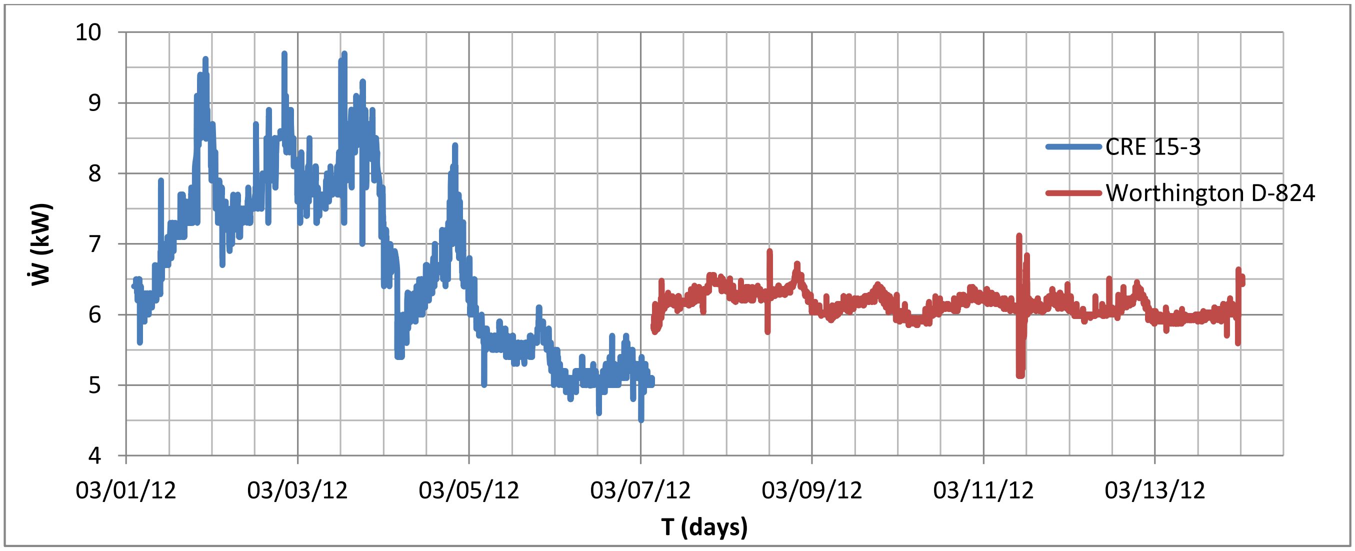


Figure 27: Grundfos CRE 15-3 vs. Worthington D-824 Power Consumption for March 1-14, 2012

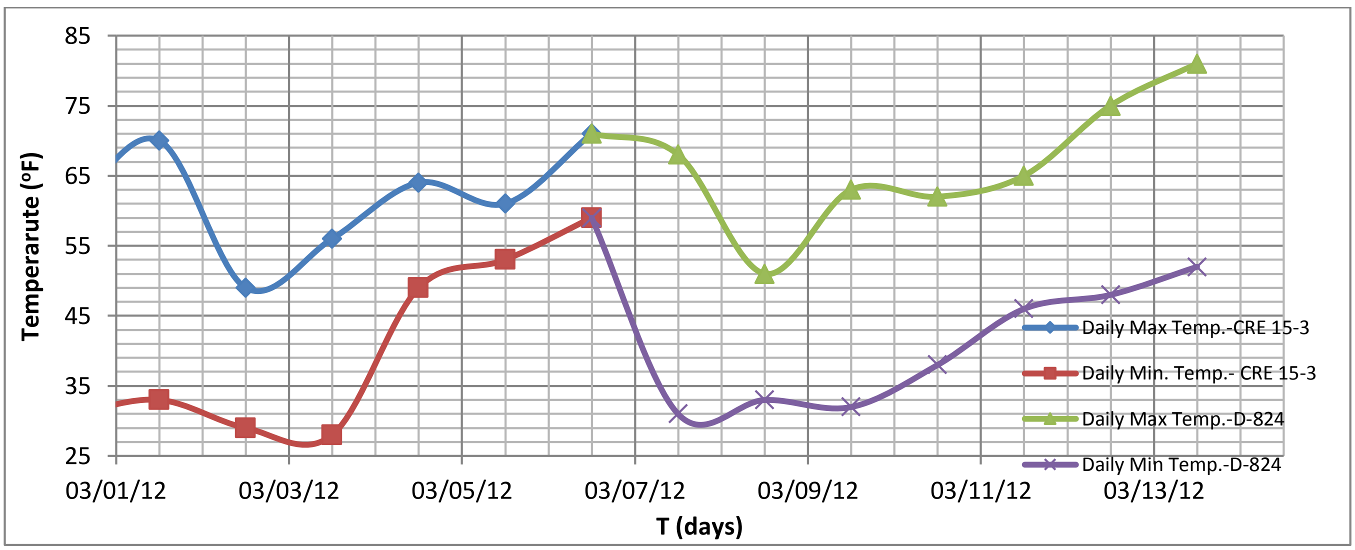


Figure 27a: Daily Maximum and Minimum Ambient Temperatures for March 1-14, 2012

For the period of March 1 (Thursday) through March 14 (Wednesday) of 2012, Fig. 27 shows the power consumption of the Grundfos CRE 15-3 and the Worthington D-824 pumps, where the Grundfos CRE 15-3 ran from March 1 through March 7 and the Worthington D-824 ran from March 7 through March 14. The average power consumption for the period that the Grundfos CRE 15-3 pumps ran was 6.64 kW while the power consumption for the Worthington D-824 was 6.14 kW. Figure 27 shows the Grundfos pumps had a greater power consumption than the Worthington constant speed pump during its first four days of operation that week. This was due to the plant's higher demand for March 1 through March 5 as Fig. 28 shows flow rates higher than 200 GPM for most of those dates due to colder weather.

The minimum and maximum outside temperature measurements for the period of March 1 through March 14 of 2012 are shown in Fig. 27a [45]. Just as in Section 3.1.1, the increase and decrease in power consumption based on outside temperatures is a lot more noticeable during the days that the Grundfos CRE 15-3 pumps were in operation, which is assumed to be due to their variable speed capability. Even though these changes are more noticeable for the variable speed pump, one can notice how the flow rate and power consumption of both pump systems showed an increase as the outside temperatures decreased, and vice-versa; hence, showing the relationship between the power plant's water demand and the outside temperature.

As shown in Fig. 28, the average flow rate of the CRE 15-3 pumps from March 1 through March 7 was 179.1 GPM and the average flow rate of the Worthington D-824 from March 7 through March 14 was 160.3 GPM. These values show that the power plant's demand was higher during the period that the CRE 15-3 pumps ran, explaining why this time the variable speed pumps had higher power consumption when compared to the Worthington D-824.

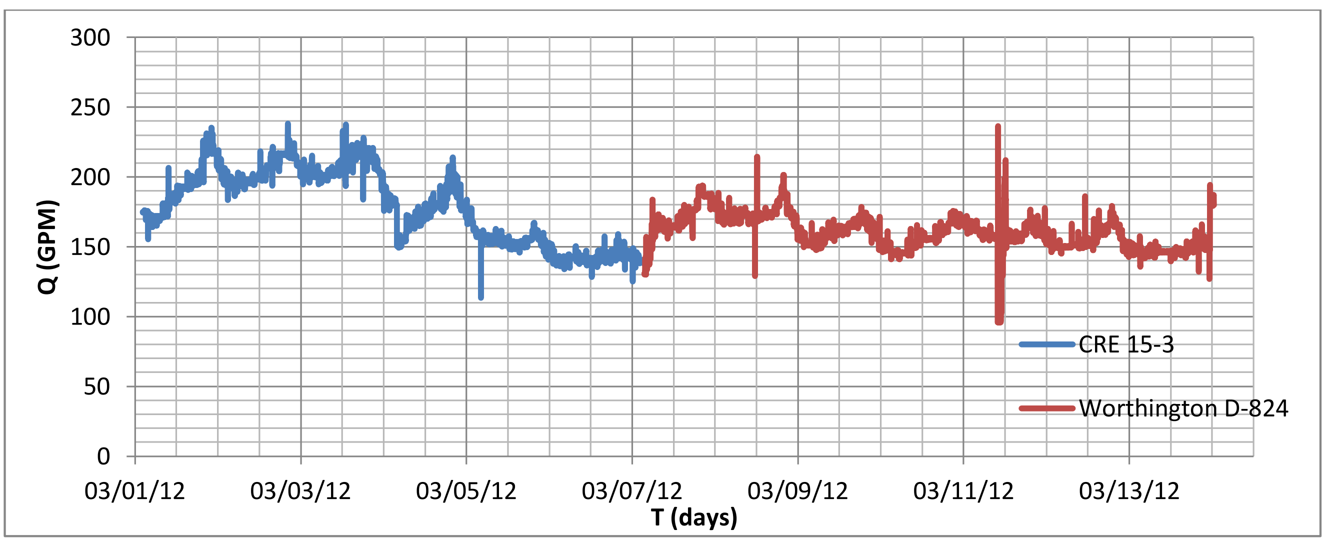


Figure 28: Grundfos CRE 15-3 vs. Worthington D-824 Flow Rate for March 1-14, 2012

Since the Grundfos CRE 15-3 pumps still had a fixed set point of 44 PSI for its discharge pressure, there was not much fluctuation when compared to the Worthington D-824 discharge pressure as is shown in Fig. 29. The average discharge pressure for the Grundfos CRE 15-3 pumps was 44.07 PSI while the average discharge pressure for the Worthington D-824 pump was 43.55 PSI.

By using the CRE 15-3 pumps' average flow rate and discharge pressure with the pump curve, the power consumption of the system was 5.98 kW, being approximately 9.94% lower than the recorded average power consumption. When following the same process with the Worthington D-824 pump curve, the power consumption obtained was 7.2 HP which is equivalent to 5.37 kW. The power consumption obtained from the Worthington D-824 pump curve is approximately 12.5% lower than the average recorded power consumption. These values show that the recorded power consumption for both variable speed and constant speed pump systems was comparable to the theoretical values obtained from their respective pump curves.

The pump and motor efficiency for the CRE 15-3 pump system at its recorded average flow rate and discharge pressure (provided by the WEBCAPS pump curve [41]) was 58.6%. The hydraulic power obtained for this pump system through the use of Eq. (5) was 7.86 HP, which is equivalent to 5.86 kW, being approximately 11.7% lower than the average recorded value. The difference between the recorded and calculated power consumption values obtained from Eq. (5) is higher than the difference between the recorded power and power consumption value found in the pump curve. However, the recorded power is still comparable to these two theoretical power consumption values.

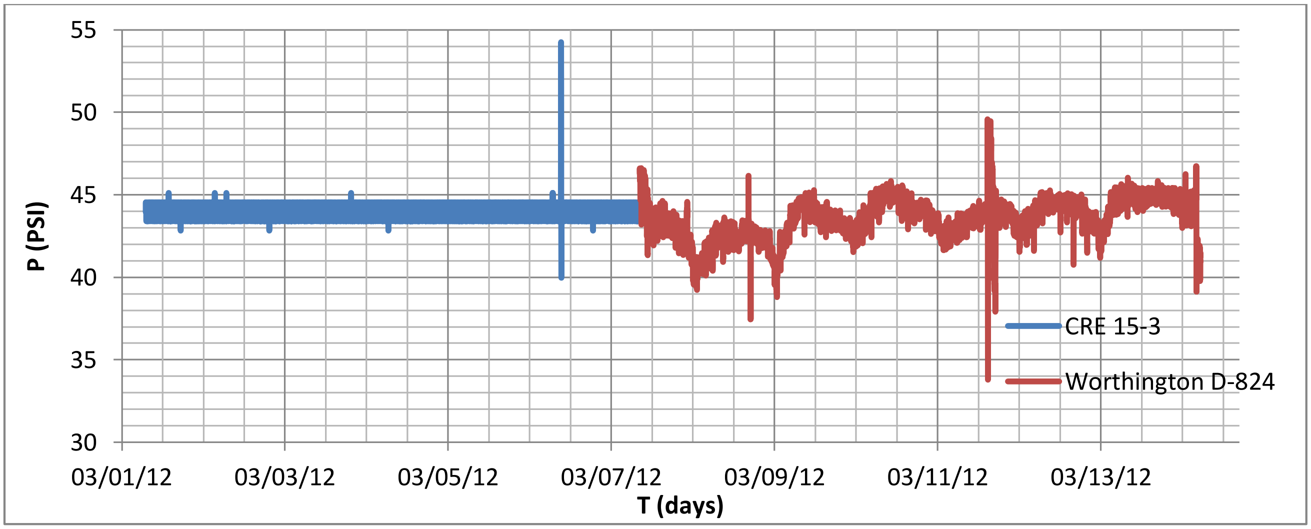


Figure 29: Grundfos CRE 15-3 vs. Worthington D-824 Discharge Pressure for March 1-14, 2012

According to its pump curve, the Worthington D-824's estimated pump efficiency at 160.3 GPM is about 63% (the reader should note that these efficiencies were estimates obtained by referring to the pump curves in Appendix B.1). Combining these values with the average discharge pressure of 43.55 PSI in Eq. (5), the hydraulic power of this pump system was 6.46 HP, or 4.82 kW, which is approximately 21.5% lower than the recorded power consumption. Again, as discussed in the results of the previous section, for the most part, it seems the constant speed pump is running at a lower efficiency shown in its pump curves since the efficiency used appears to take into consideration only the pump and not the pump and motor combined as the Grundfos pump curve does. To obtain a value comparable to the recorded power consumption through the use of Eq. (5), the pump and motor efficiency for this system is estimated to be approximately 49.5%. (The method for calculating this efficiency is explained in Section 3.1.1.) Again, this shows that the pump system is running at a lower efficiency than the one shown in its theoretical data since it seems that the pump curve does not take into consideration the combined pump and motor efficiency.

3.1.3 April 10 through April 23, 2012

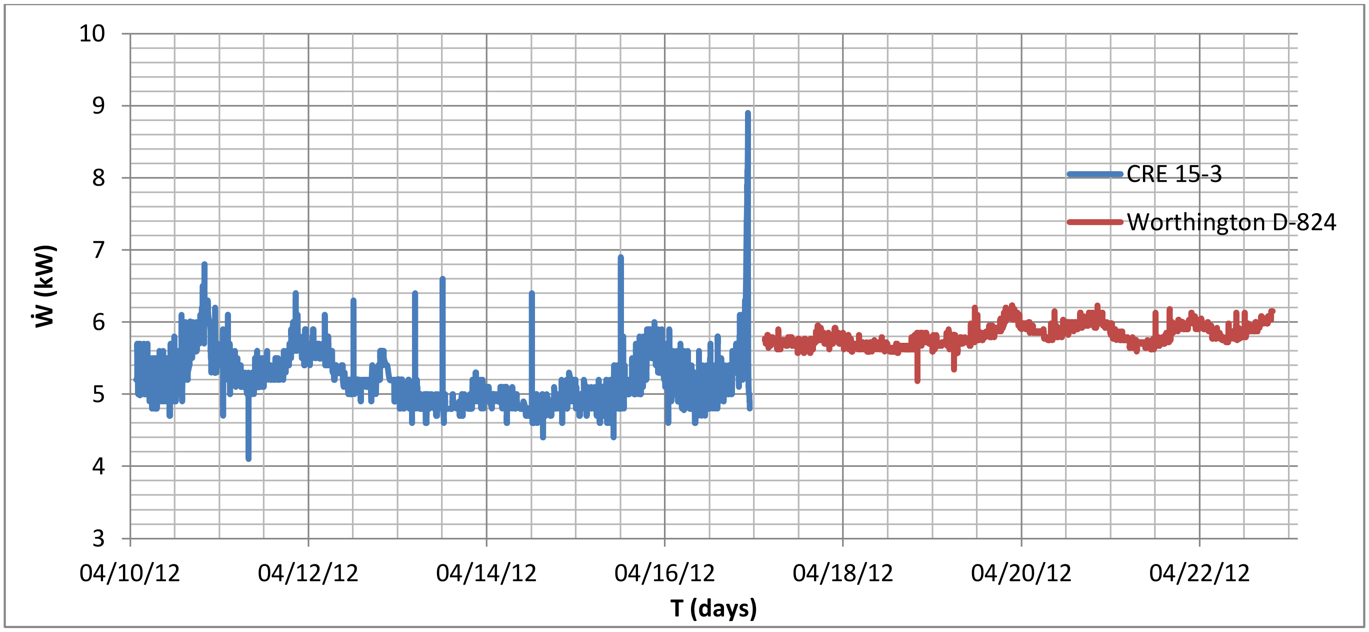


Figure 30: Grundfos CRE 15-3 vs. Worthington D-824 Power Consumption for April 10-23, 2012

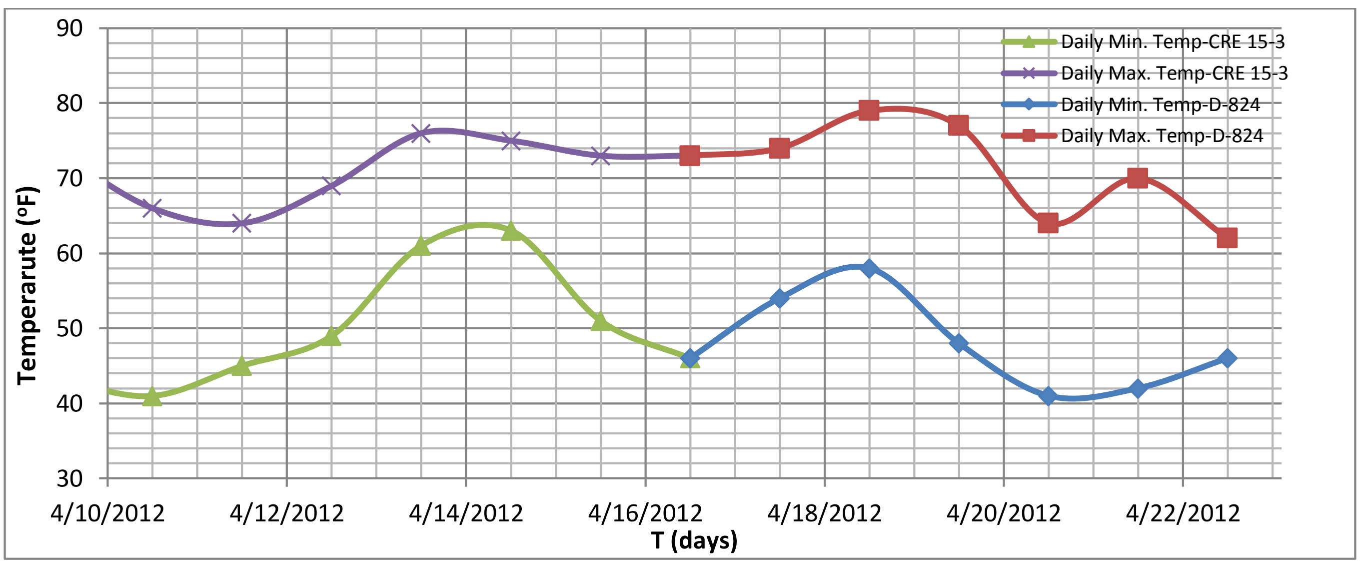


Figure 30a: Daily Maximum and Minimum Ambient Temperatures for April 10-23, 2012

With respect to the power consumption during the period of April 10 (Tuesday) through April 23 (Monday), shown in Fig. 30, the average power consumption of the Grundfos CRE 15-3 pumps from April 10 through April 17 was 5.18 kW, and the average power consumption of the Worthington D-824 pump from April 17 through April 23 was 5.81 kW, which shows that, for this period, both pump systems had fairly comparable power consumptions. Also, these power consumption values were lower than the ones discussed in the previous results, which can be explained by the higher temperatures (which varied between high 40s to low 80 degrees Fahrenheit) shown in Fig. 30a [45]. Since the steam demand of the plant was lower during this period because of warmer weather, this caused the flow rate of water supplied to the system to also be smaller (shown in Fig. 31), making both pump systems have smaller power consumption.

The average flow rates of the Grundfos CRE 15-3 and the Worthington D-824 pumps for the period shown in Fig. 31 were 141.77 GPM and 138.89 GPM, respectively. The average discharge pressure from the data found in Fig. 32 was 45.57 PSI for the Worthington D-824 and 44.09 PSI for the Grundfos CRE 15-3.

The values of the average flow rate and discharge pressure of each pump system can be used with their respective pump curves to obtain the theoretical power consumption values for comparison with the values obtained via data gathering. The power consumption found from examining the CRE 15-3 pump curve of App. B.2 was 4.73 kW. This value is very close to the average power consumption obtained through data gathering, since it is 8.69% lower than the recorded 5.18 kW.

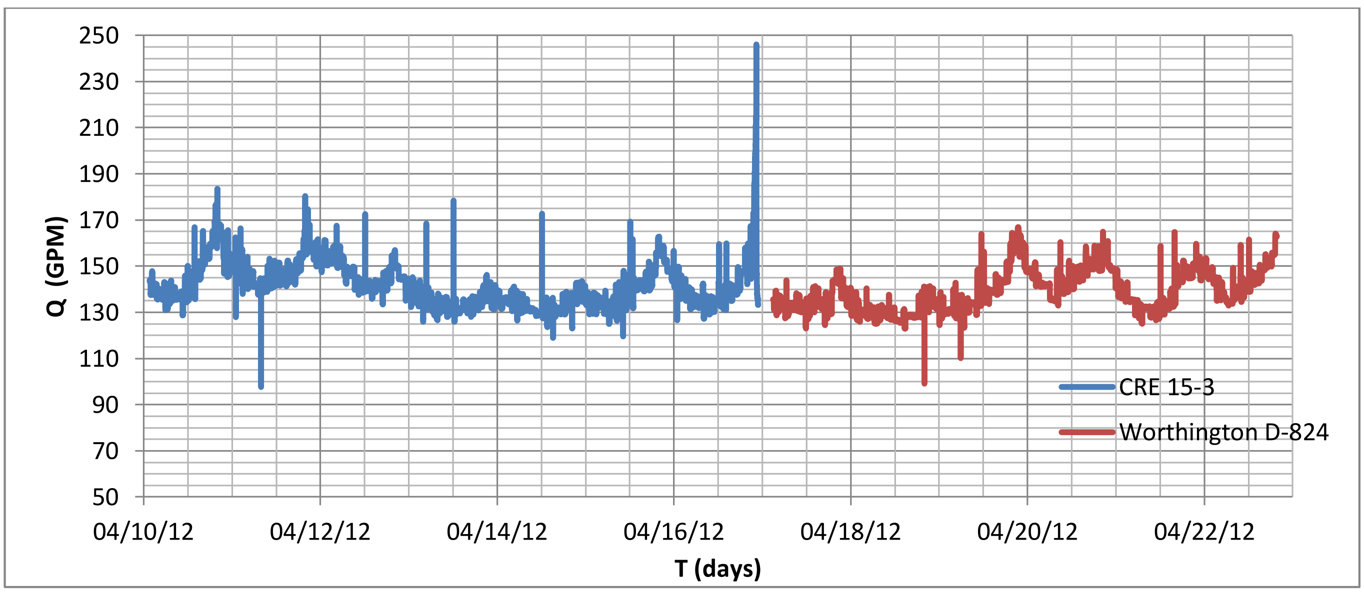


Figure 31: Grundfos CRE 15-3 vs. Worthington D-824 Flow Rate for April 10-23, 2012

The power consumption taken from the Worthington pump curve was 6.8 HP, which is equivalent to 5.07 kW. This theoretical value is 12.7% lower than the recorded value, showing how the value obtained through the data gathering system is still comparable to the theoretical pump data.

The pump and motor efficiency found in the Grundfos CRE 15-3 WEBCAPS pump curve at the average flow rate 141.77 GPM and discharge pressure 44.08 PSI was 58.7% [41]. Inputting these values into Eq. (5), the calculated power consumption was 6.21 HP which is equivalent to 4.63 kW. This value is 10.6% lower than the experimentally determined value, which again shows that the gathered data is still close to this theoretical value.

According to the Worthington D-824 pump curve, its estimated efficiency at 138.89 GPM is approximately 57% (refer to the first plots in Appendix B.1). Using these values with Eq. (5), the hydraulic power was 6.47 HP, or 4.83 kW, which is 16.9% lower than the experimentally determined power. This means that, given the average recorded flow rate and discharge pressure of the Worthington D-824, to get an estimated hydraulic power from Eq. (5) equal to the recorded power, the pump efficiency should be 47.4% instead of 57%. All experimentally determined power consumption values discussed so far are fairly close to the values found on their respective pump curves. For this reason, it is believed that this is sufficient proof that this project can use the experimentally determined power consumption values for comparison of the CRE 15-3 and Worthington D-824 pump systems.

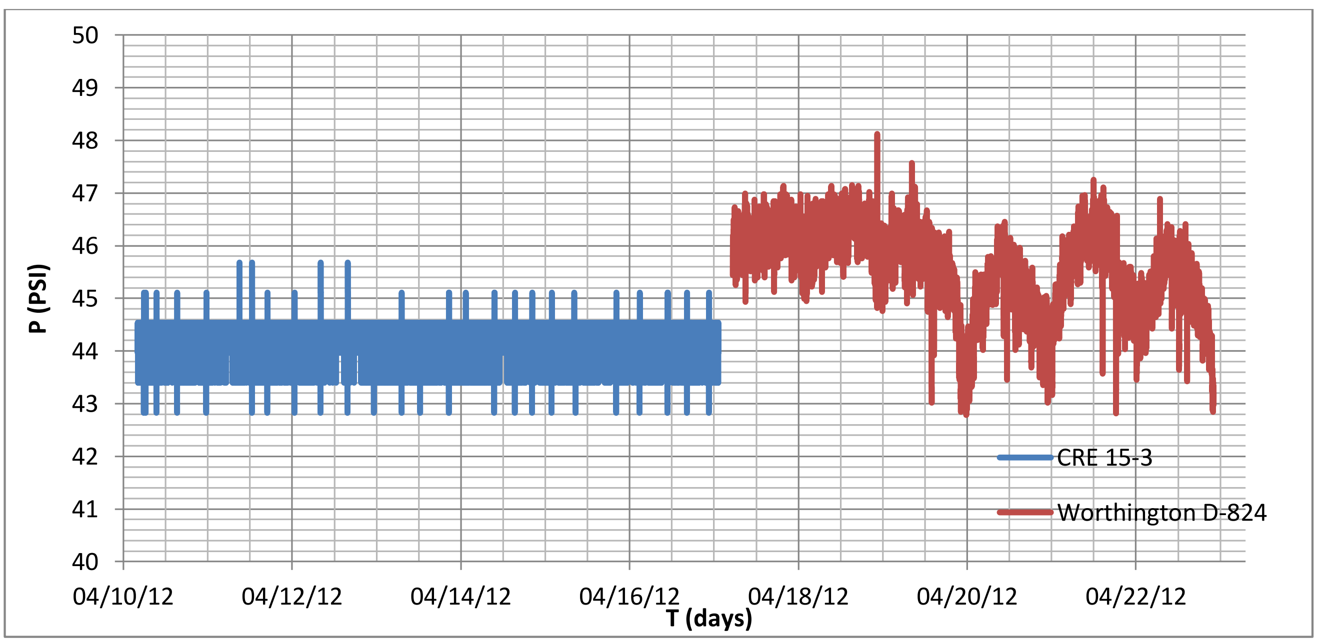


Figure 32: Grundfos CRE 15-3 vs. Worthington D-824 Discharge Pressure for April 10-23, 2012

Figure 33 is an example of the differential pressure across the control valve when the Worthington D-824 is operating and when the Grundfos CRE 15-3 system is running in discharge pressure mode. For this specific period of time, the average differential pressure across the control valve when running the CRE 15-3 was 32 PSI, and when running the Worthington D-824 it was 34.15 PSI. This shows that the control valve behaves similarly for both pumps when the CRE 15-3 is running in discharge pressure mode. The pressure in the outlet side of the valve, i.e., inside the deaerator tank, is approximately 9 PSI. Hence, the control valve drops whatever pressure it receives at its inlet to 9 PSI, and that pressure drop is recorded as the differential pressure shown in Fig. 33. This differential pressure data is not crucial information given the scope of this project (hence, just a few results for each case will show this differential pressure information); but it is necessary just to show that such a pressure drop exists when running the pumps in discharge pressure mode, and that the control valve helps to maintain the pressure before the deaerator tank so that the water has enough pressure to reach the heat exchanger located on the first floor of the power plant (the heat exchanger will be taken into consideration in Section 3.2).

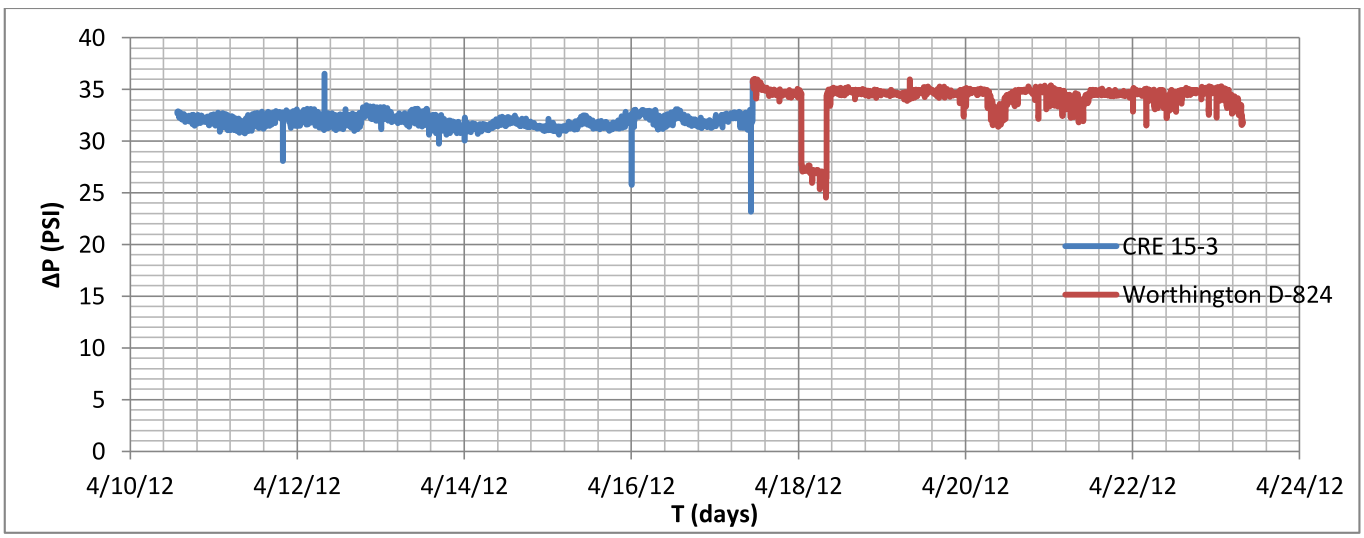


Figure 33: Grundfos CRE 15-3 vs. Worthington D-824 Differential Pressure across Control Valve for April 10-23, 2012

3.1.4 April 24 through May 8, 2012

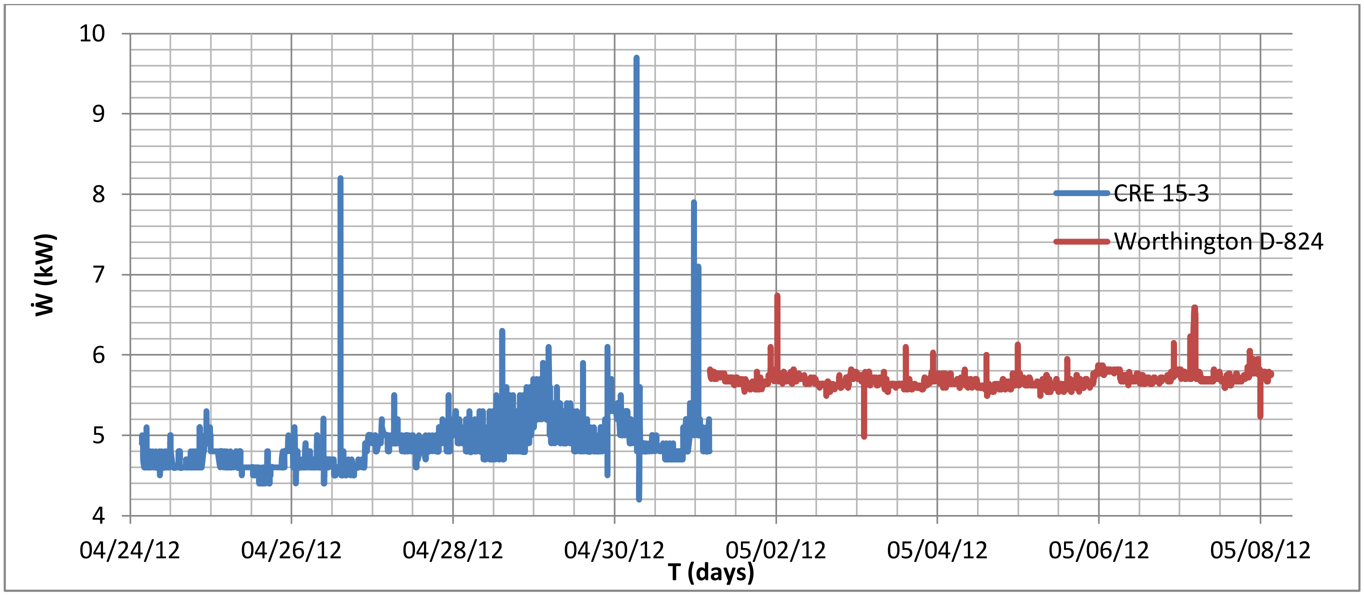


Figure 34: Grundfos CRE 15-3 vs. Worthington D-824 Power Consumption for April 24-May 8, 2012

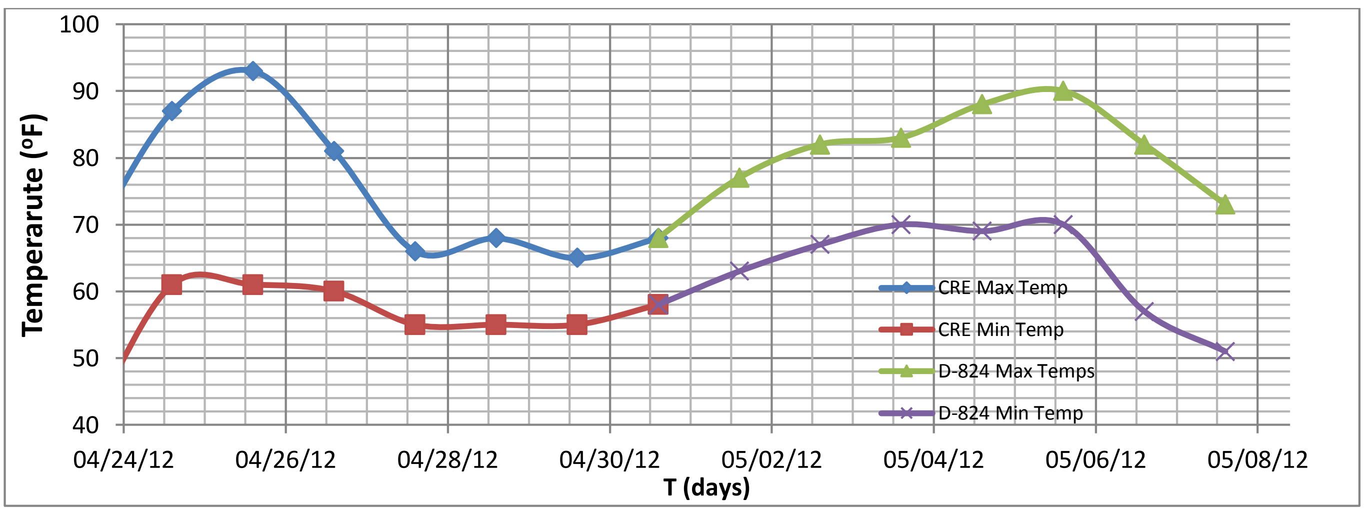


Figure 34a: Daily Maximum and Minimum Ambient Temperatures for April 24 through May 14, 2012

In the period of April 24 (Tuesday) through May 8 (Tuesday), the Grundfos CRE 15-3 pumps ran from April 24 through May 1, having an average recorded power consumption of 4.86 kW; and the Worthington D-824 pump ran from May 1 through May 8 with an average recorded power consumption of 5.67 kW as shown in Fig. 34. Again, the warmer weather helped reduce the steam demand of the power plant, consequently reducing the power consumption of the pumps providing water to the system. Figure 34a shows the minimum and maximum outside temperatures and fluctuations for the period of April 24, 2012 through May 8, 2012 [45]; from which one can notice a relationship between warmer weather and lower power consumptions and flow rates. (For more data on the average temperature for the periods discussed, see Appendix D.)

The average flow rate for the CRE 15-3 pump system for the period shown in Fig. 35 was 132.28 GPM, and the average flow rate for the Worthington D-824 pump system was 130.72 GPM. These averages show that, for this period of time, both pumps system provided very similar flow rates of water to the system. However, the CRE 15-3 pumps consumed a smaller amount of power when compared to the Worthington D-824 constant speed pump.

The average discharge pressure of the Grundfos CRE 15-3 pumps (from Fig. 36) was 44.07 PSI, while the discharge pressure for the Worthington D-824 pump was 46.19 PSI. Using these values in each pump's respective curves, their theoretical power consumption was 4.73 kW for the CRE 15-3 pumps and 4.87 kW for the Worthington D-824 pump. (The extra significant digits were obtained by using the WEBCAPS pump curves for the Grundfos pumps [41], and by converting horsepower information into kW for the Worthington Pump.) Again, this shows that the recorded power consumption values were close to the theoretical values, being within 2.67% (for the CRE 15-3 pumps) and 14.1% (for the Worthington D-824 pump) of each other.

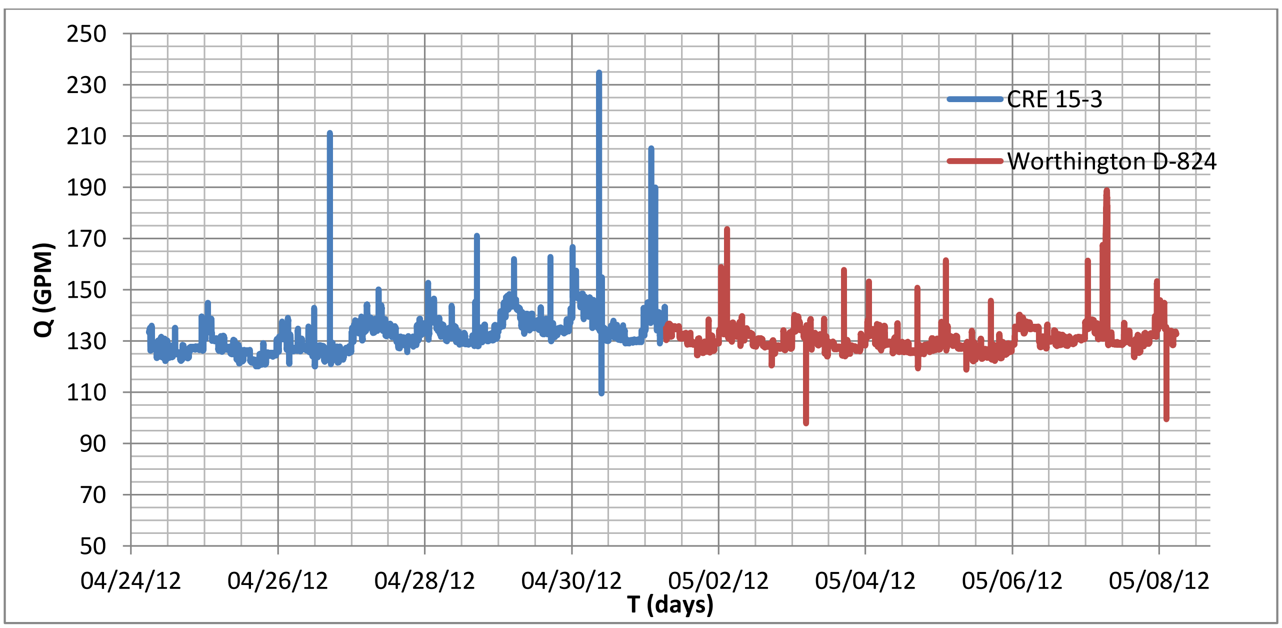


Figure 35: Grundfos CRE 15-3 vs. Worthington D-824 Flow Rate for April 24-May 8, 2012

The pump and motor efficiency of the Grundfos CRE 15-3 pump system at a 132.28 GPM flow rate and a 44.07 PSI discharge pressure was 58.1% (obtained from the Grundfos' WEBCAPS pump curves [41]). The calculated hydraulic power for this pump system using Eq. (5) was 4.36 kW (5.85 HP), which is 10.3% lower than the recorded average power consumption. According to its curve, the Worthington D-824 pump has an approximate pump efficiency of 55% at a 130.72 GPM flow rate. Using this information, Eq. (5) gives a hydraulic power of 4.77 kW (6.40 HP), which is 15.9% lower than the recorded power consumption. Hence, for the calculated hydraulic power to be the same as the recorded power consumption, the pump and motor efficiency for the Worthington D-824 should be approximately 45.5%.

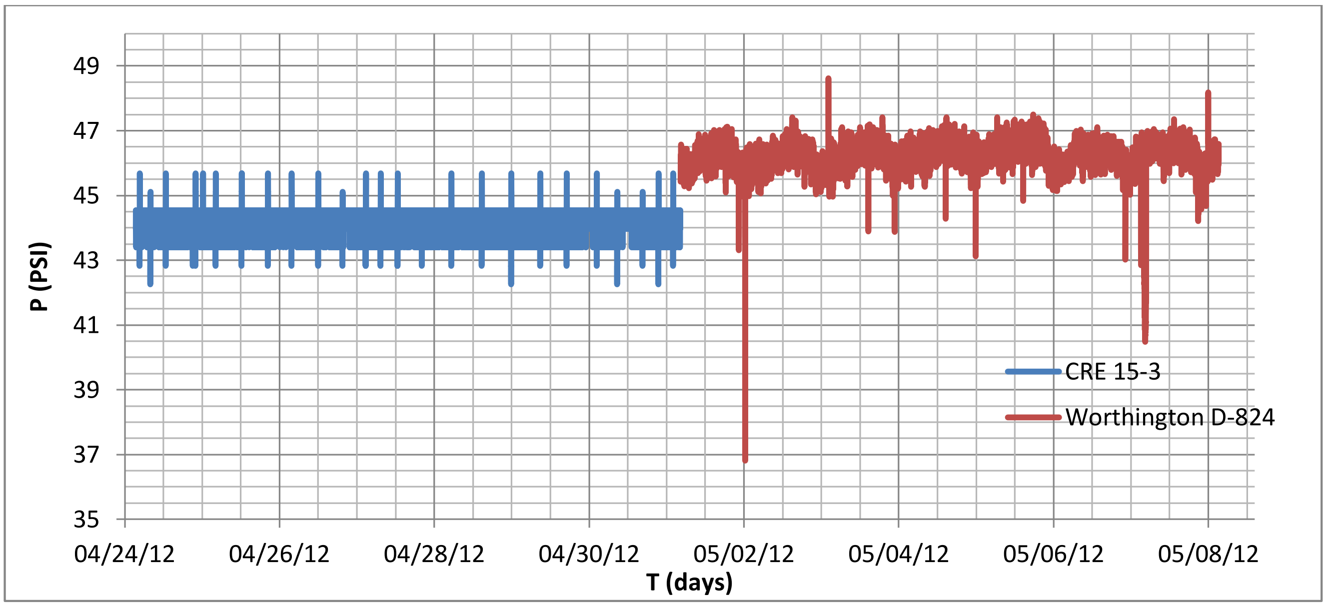


Figure 36: Grundfos CRE 15-3 vs. Worthington D-824 Discharge Pressure for April 24-May 8, 2012

As Fig. 37 shows, the differential pressure across the control valve was lower for the period when the CRE 15-3 pumps were running; however, the pressure remained fairly consistent for the entire period of operation of both pumps. The average differential pressure for the period that the CRE 15-3 pumps ran was 31.48 PSI, and for the period that the Worthington D-824 pump ran, it was 34.07 PSI.

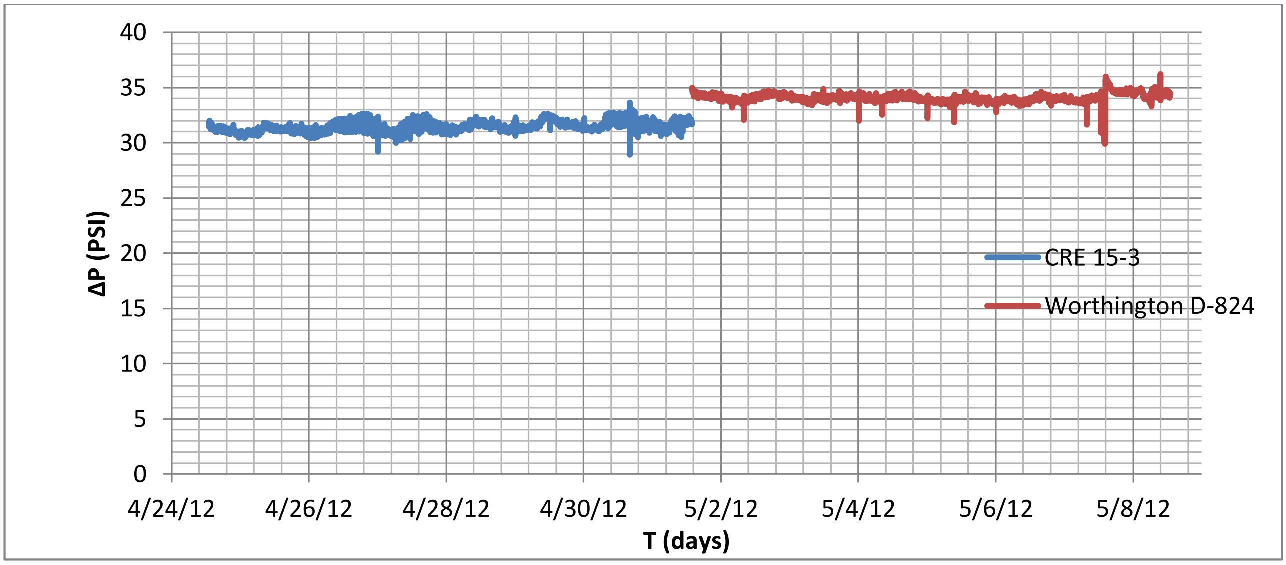


Figure 37: Grundfos CRE 15-3 vs. Worthington D-824 Differential Pressure across Control Valve for April 24-May 8, 2012

3.2 Case 2

3.2.1 April 15, 2013

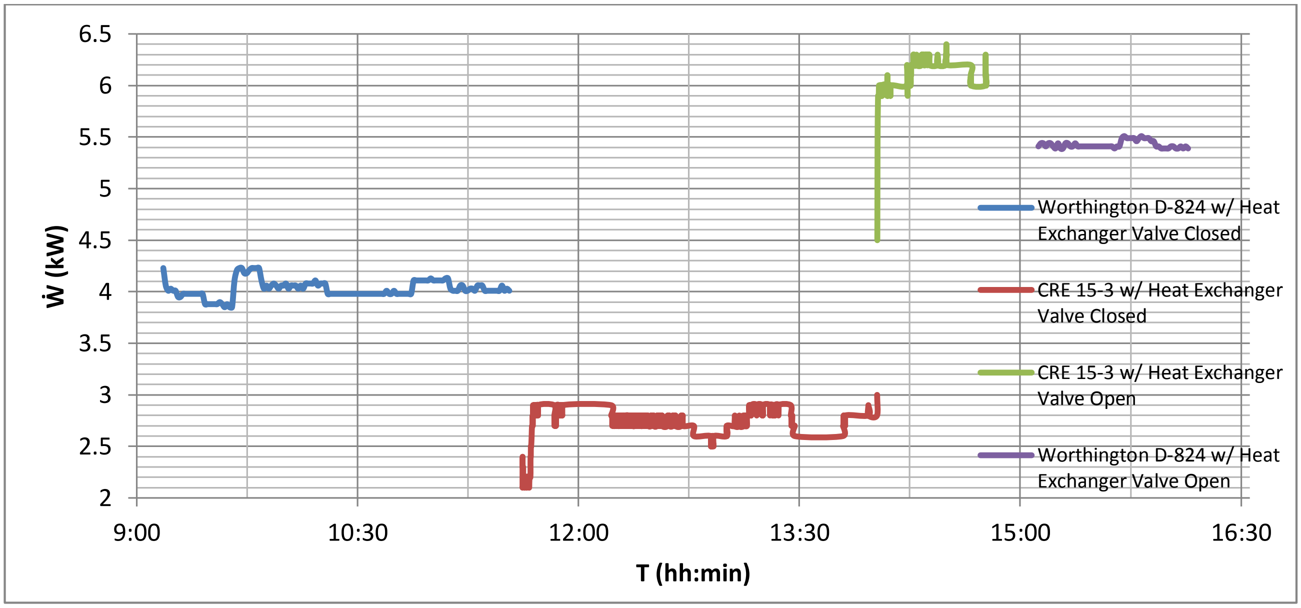


Figure 38: Grundfos CRE 15-3 vs. Worthington D-824 Power Consumption for April 15, 2013.

For this set of results, each set of pumps ran for approximately two and a half hours with the heat exchanger valve (located in the first floor of the power plant) closed and then approximately one hour with the heat exchanger valve opened. This was done in order to check how the power consumption, flow rate and discharge pressure of each pump differed when excluding the heat exchanger from the system.

Figure 38 shows how both pump systems consumed much less energy when they did not provide water to the heat exchanger. When the valve to the heat exchanger was closed, the average recorded power consumption was 4.03 kW for the Worthington D-824 pump and 2.74 kW for the Grundfos CRE 15-3 pumps. Even though Fig. 39 shows that the Worthington D-824 pump had a lower average flow rate when compared to the Grundfos CRE 15-3 pumps (69.19 GPM versus 78.08 GPM), the constant speed pump still consumed 32% more energy than the Grundfos variable speed pumps. Figure 39 shows that the discharge pressure for the Worthington D-824 was much higher when the valve to the heat exchanger was closed as compared to when it was open.

The pressure increase happened because, once water was no longer able to reach the heat exchanger, all of the water was now supplied to the deaerator tank. This caused the control valve to close more, creating more resistance in the system that forced the constant speed pump to increase its discharge pressure in order to provide the required flow rate to the system. It must be remembered that the Grundfos CRE 15-3 pumps were configured to run in discharge pressure mode with a set point of 43 PSI for Case 2, so its discharge pressure did not fluctuate as much again since it just maintained its set point value by reducing its speed when the control valve restricted the flow into the deaerator tank. The average discharge pressure for the period with the heat exchanger valve closed in Fig. 40 was 49.25 PSI for the Worthington D-824 pump and 42.99 PSI for the Grundfos CRE 15-3 pumps.

Given the average flow rate and discharge pressure for both pump systems, the Grundfos CRE 15-3 pump curve theoretical power consumption was 2.53 kW, being about 7.66% lower than the recorded value. The Worthington D-824 pump curve theoretical power was approximately 4.10 kW (5.5 HP), being approximately 1.74% higher than the recorded results. Therefore, this shows how the gathered values are still comparable to the theoretical pump curve values and how the constant speed pumps consumed more power than the variable speed pumps while the heat exchanger was not used.

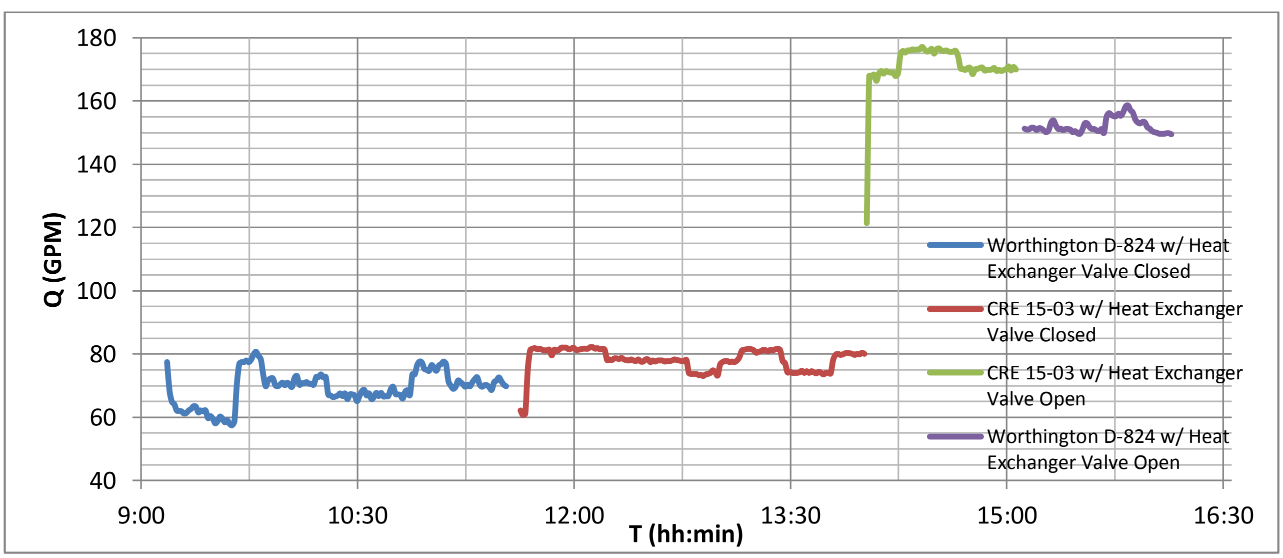


Figure 39: Grundfos CRE 15-3 vs. Worthington D-824 Flow Rate for April 15, 2013.

The Grundfos CRE 15-3 pump and motor efficiency at a 78.08 GPM flow rate is approximately 58.9% [41]. The calculated hydraulic power found through Eq. (5) was 2.48 kW (3.326 HP), which was about 9.49% lower than the recorded value. The Worthington D-824 pump efficiency at a 69.19 GPM flow rate was approximately 35%, resulting in a calculated hydraulic power of 4.23 kW (5.67 HP), approximately 4.96% higher than the recorded power consumption. Hence, the recorded power consumptions for the period that the heat exchanger valve was closed for both pump systems were very close to their theoretical and calculated values. In Case 1, the theoretical power consumption values for the Worthington D-824 pump were all lower than the recorded results. A possible reason why the calculated theoretical values for the Worthington pump in Case 2 (for the times when the heat exchanger valve was closed) are higher than the recorded power consumptions could be the combination of lower estimated pump efficiencies at lower flow rates and the higher discharge pressure being used in Eq. (5) when the heat exchanger valve was closed. However, all theoretical values are still comparable to the recorded values.

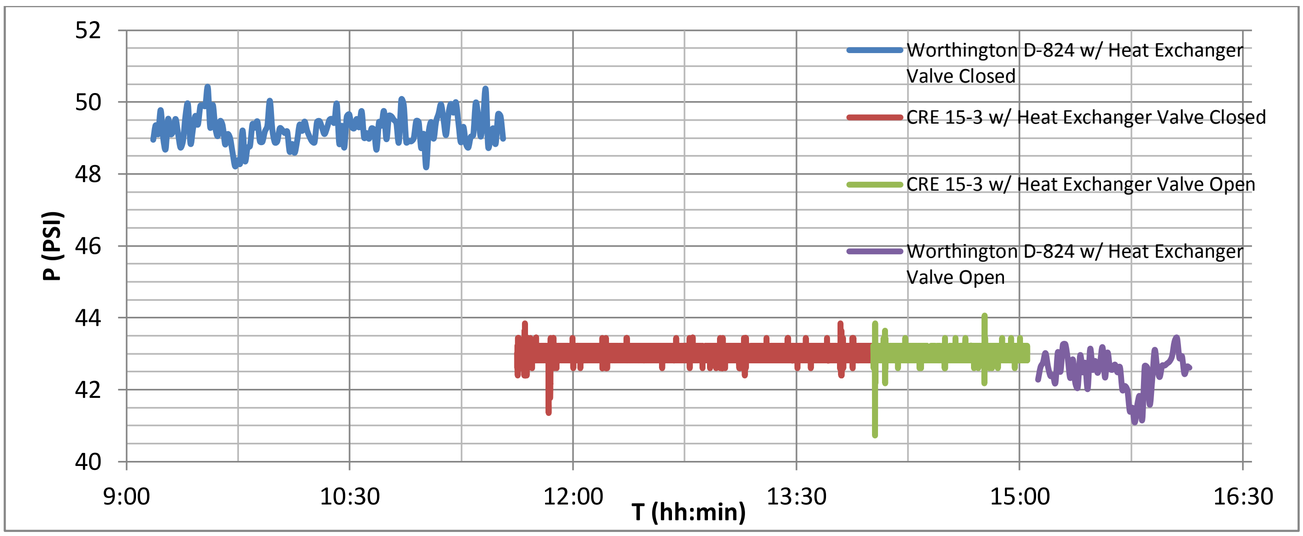


Figure 40: Grundfos CRE 15-3 vs. Worthington D-824 Discharge Pressure for April 15, 2013.

For the period in which the heat exchanger valve was open, the average power consumption was 6.07 kW for the Grundfos CRE 15-3 and 5.43 kW for the Worthington D-824. The average flow rate for the CRE 15-3 and the Worthington D-824 pumps were 171.2 GPM at an average 42.99 PSI discharge pressure and 152.2 GPM at an average 42.51 PSI discharge pressure, respectively. In this set of results, the variable speed pump had to provide a higher flow rate, and consequently a higher power consumption, to “feed” the heat exchanger when compared to the constant speed pump. This also shows how the heat exchanger causes the pumps to consume a lot more power when compared to the period which the heat exchanger valve was closed.

The CRE 15-3 pump curve's theoretical power consumption value at the average flow rate and discharge pressure was 5.57 kW, being about 8.24% lower than the recorded power consumption. The theoretical power consumption value from the Worthington D-824 pump curves was approximately 5.22 kW (7 HP), about 3.87% lower than the recorded consumption. Hence, the theoretical values obtained from the pump curves of both pump systems were very comparable to the power consumption values obtained via data gathering.

The calculated pump hydraulic power for the CRE 15-3 pump system with pump and motor efficiency of 58.7% (obtained from the pump curve's WEBCAPS version [41]) at the 171.24 GPM flow rate was 5.45 kW (7.31 HP), about 10.2% lower than the recorded consumption. Regarding the Worthington D-824 pump, its theoretical pump efficiency at 152.2 GPM is approximately 60%, resulting in a calculated pump hydraulic power of 4.69 kW (6.29 HP), about 13.6 % lower than the recorded consumption. Therefore, so that the calculated power consumption be similar to the recorded Worthington D-824 power consumption, the pump and motor efficiency should be approximately 51.8 % instead of a pump efficiency of 60%.

3.2.2 April 16, 2013

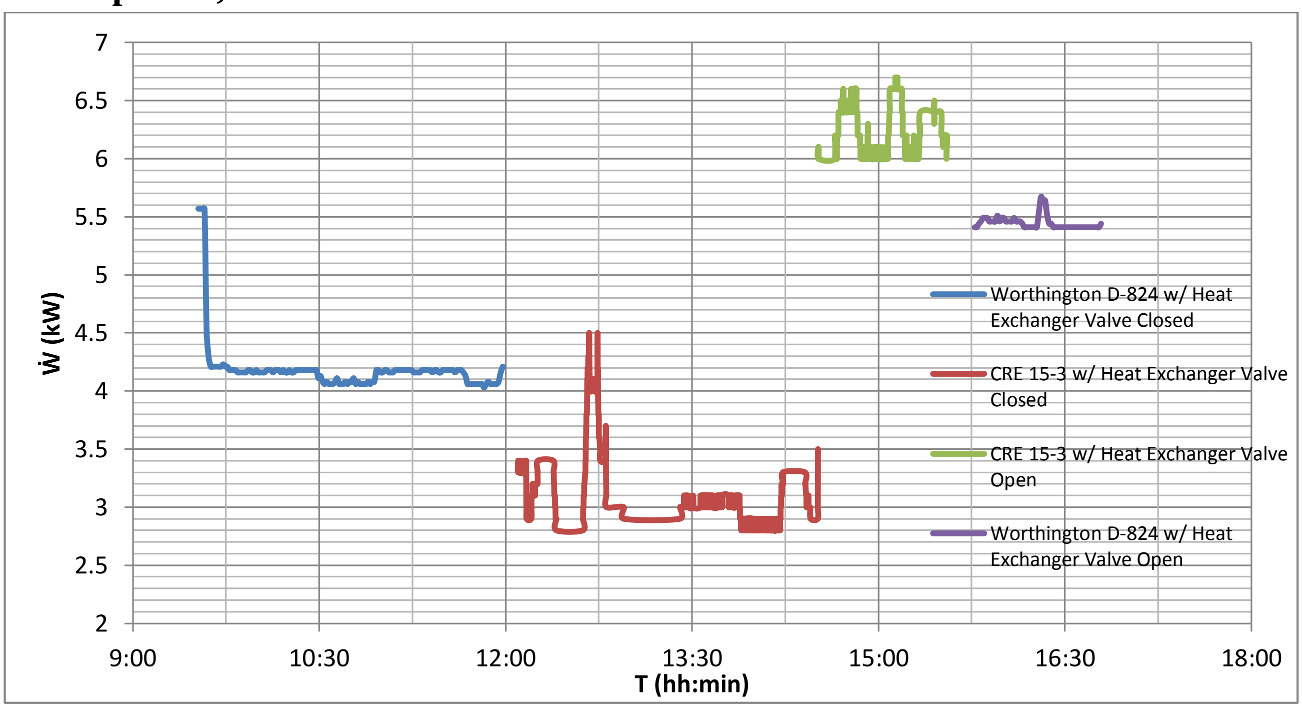


Figure 41: Grundfos CRE 15-3 vs. Worthington D-824 Power Consumption for April 16, 2013.

The average recorded power consumption for the period shown in Fig. 41 in which the heat exchanger access valve was closed was 4.14 kW for the Worthington D-824 pump and 3.09 kW for the Grundfos CRE 15-3 pumps. With respect to the period in which the heat exchanger access valve was open, the CRE 15-3 and Worthington D-824 pumps' recorded power consumptions were 6.21 kW and 5.45 kW, respectively. Again, these results show how the variable speed pumps consume less power than the constant speed pump when the water is just delivered to the deaerator tank (which was the primary focus in the beginning of this project). However, the Grundfos pumps tend to consume more energy when water is supplied to both the deaerator tank and the heat exchanger. This could be due to the fact that the variable speed pump system has a high head capacity but a low flow capacity, which caused it to work harder than usual and consume much more power when it needed to provide greater flow rates to the system; and when the flow requirements were small, it was able fulfill that demand with much less power.

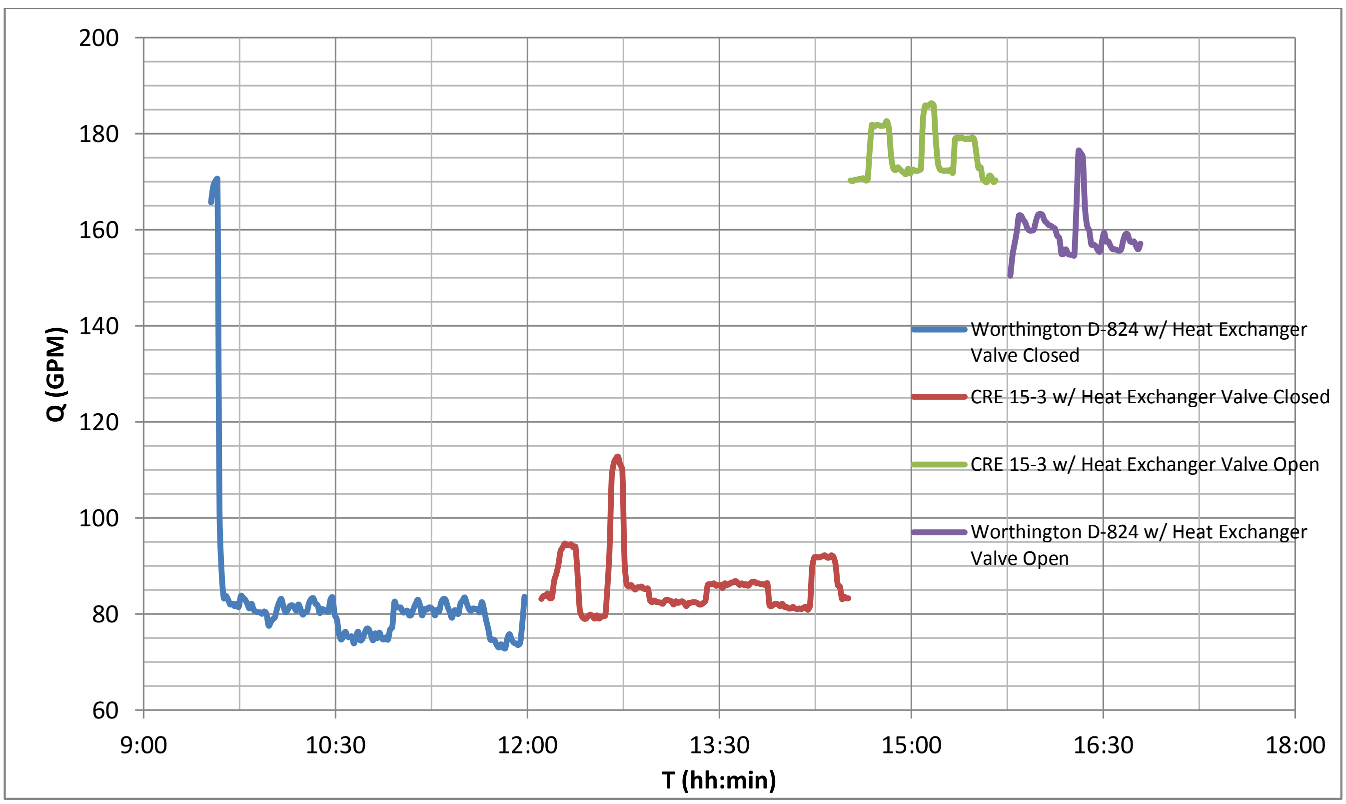


Figure 42: Grundfos CRE 15-3 vs. Worthington D-824 Flow Rate for April 16, 2013.

Given the flow rates displayed in Fig. 42, during the period in which the access valve to the heat exchanger was closed, the Worthington D-824 pump provided an average 79.5 GPM to the system, while the Grundfos CRE 15-3 pumps provided an average 86.1 GPM. The corresponding average discharge pressures shown on Fig. 43 were 48.8 PSI for the Worthington D-824 pump and 43 PSI for the Grundfos CRE 15-3 pumps. When the access valve to the heat exchanger was opened, those average flow rates changed to 159.3 GPM with a discharge pressure of 42.2 PSI for the Worthington pump and 175.6 GPM with a 42.99 PSI discharge pressure for the Grundfos pumps.

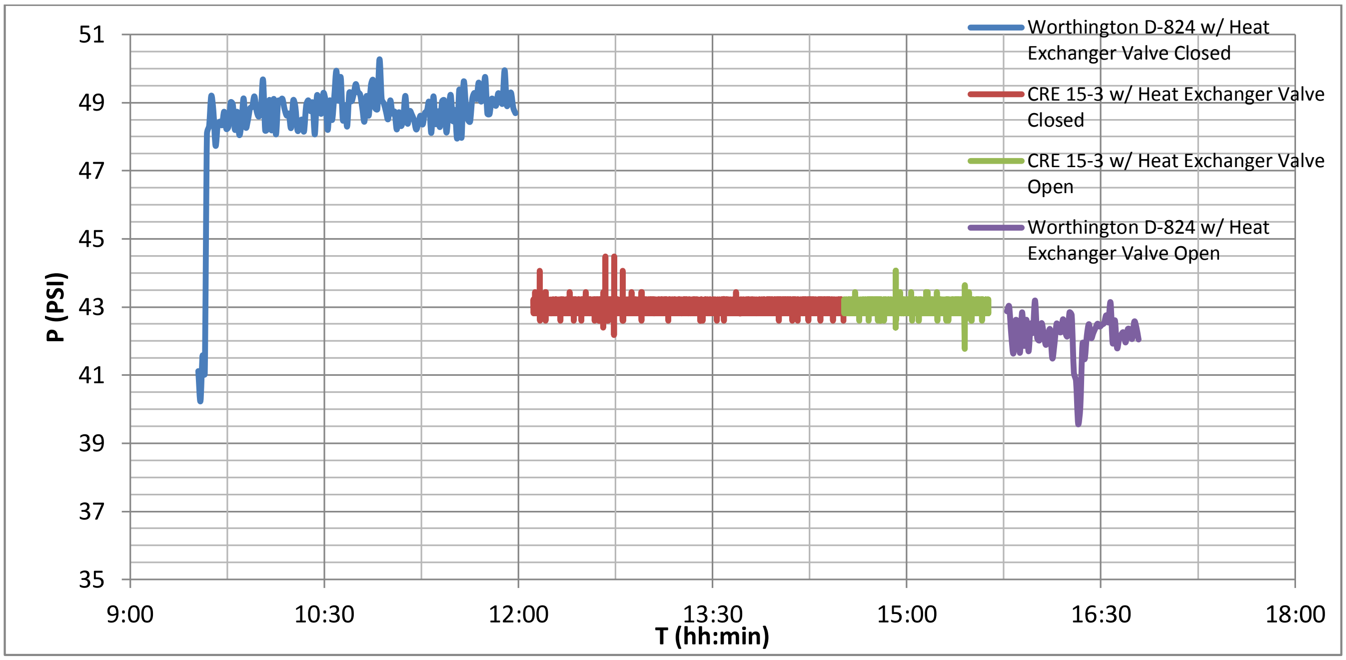


Figure 43: Grundfos CRE 15-3 vs. Worthington D-824 Discharge Pressure for April 16, 2013.

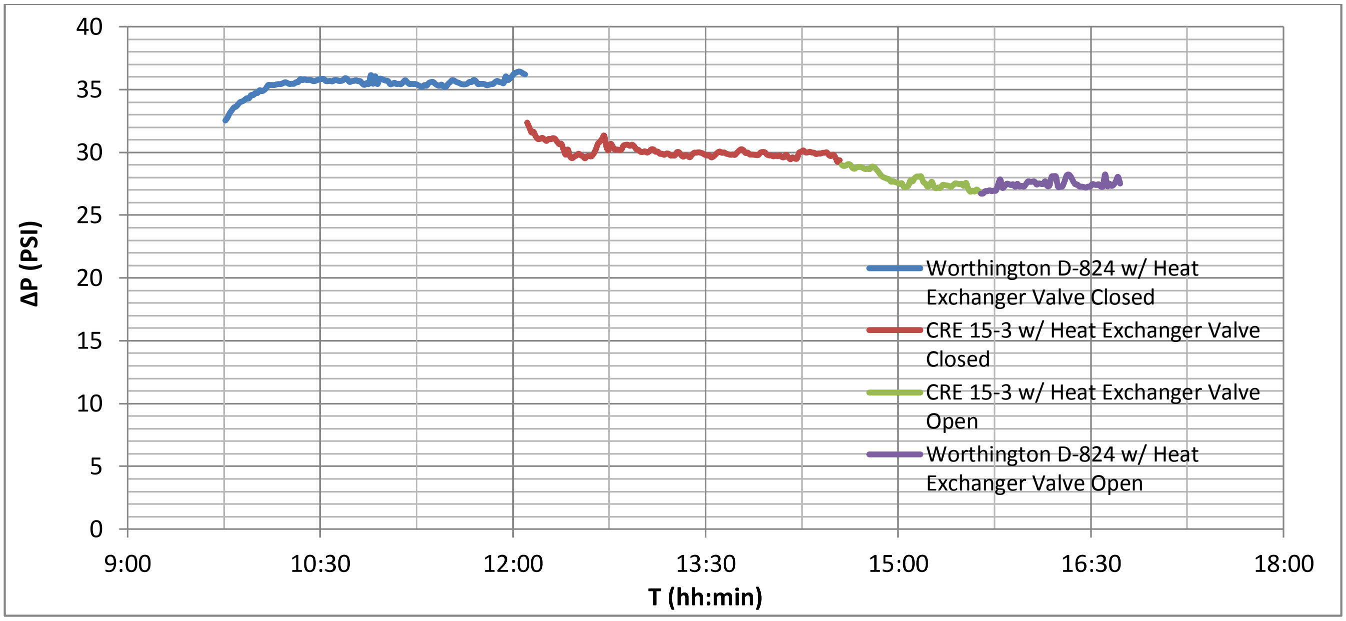


Figure 44: Grundfos CRE 15-3 vs. Worthington D-824 Differential Pressure across Control Valve for April 16, 2013.

Figure 44 shows the differential pressure across the control valve for both pump systems when they are running with the heat exchanger access valve open and closed. One can notice that, when the heat exchanger valve is closed and the Worthington D-824 pump is in operation, the differential pressure is slightly higher than when the valve is open. This correlates to the higher discharge pressure that this pump had when running with the heat exchanger valve closed, where the average differential pressure across the valve was 35.4 PSI. When the heat exchanger access valve was opened, the differential pressure across the control valve dropped to an average 27.45 PSI while the Worthington D-824 pump was in operation, because its discharge pressure also dropped. Since the Grundfos CRE 15-3 pumps have a set-point pressure when running in discharge pressure mode, i.e., independently of the heat exchanger valve being open or closed, the pumps maintain the same discharge pressure. Figure 44 shows how the differential pressure across the control valve remained nearly the same when the CRE 15-3 pumps were in operation. The average differential pressure for the time that the Grundfos CRE 15-3 pumps were operating with the heat exchanger access valve closed was 30.11 PSI, and was 27.88 PSI when the access valve was open.

The theoretical power consumption value obtained from the Grundfos CRE 15-3 pump curves using the previously mentioned flow rates and discharge pressures was 2.8 kW for the period when the heat exchanger was unused, being just under 9.39% of the recorded power consumption. For the period when the heat exchanger was in use, the theoretical power consumption was 5.71 kW, which was about 8.05% lower that the recorded power consumption. With the use of Eq. (5) and a pump and motor efficiency of 58.7% [41], the calculated pump hydraulic power for the Grundfos CRE 15-3 pumps during the period with no heat exchanger was 2.74 kW (11.3% lower than the recorded value); and for the period when the heat exchanger was in use, using a pump and motor efficiency of 58.5% [41], the calculated pump hydraulic power was 5.62 kW (9.5% lower than the recorded power consumption).

The Worthington D-824 pump curve showed an approximate 5.5 HP, or 4.10 kW, theoretical power for the period with the heat exchanger access valve closed, i.e., approximately 1% lower than the recorded value, and approximately 7.1 HP, or 5.29 kW, theoretical power when the heat exchanger access valve was open (2.93% lower than the recorded power consumption). The pump efficiencies shown in the Worthington D-824 horsepower curve (Appendix B.1) for when the heat exchanger access valve was closed and opened were approximately 38% and 61%, respectively. Using these efficiencies and their respective flow rates and discharge pressures in Eq. (5), the average calculated pump hydraulic power for the Worthington D-824 was about 5.65 HP, i.e., about 4.21 kW (about 1.7% higher than the recorded consumption), for the period with the heat exchanger not used and about 6.43 HP, or 4.79 kW (nearly 12.1% lower than the recorded consumption) for the period with the heat exchanger in operation.

It seemed that the efficiency of the Worthington D-824 pump when the heat exchanger was not in operation was low enough to have the hydraulic power comparable to the recorded power consumption. However, when the heater exchanger was in operation, the difference between the recorded and calculated power increased about 12.1%. This could mean that the combined pump and motor efficiency (not shown in the pump curves) is similar to just the pump efficiency at lower flow rates, but at higher flow rates, it plays a bigger role since the motor is having to do more work with the pump, dropping the system overall efficiency. For this reason, in order for the calculated average hydraulic power be the same as the average recorded power, given the average flow rates and discharge pressures, the pump and motor efficiency should be approximately 53.6% for the period during which the heat exchanger was in operation. Nevertheless, even without this “recalculated efficiency” for the Worthington D-824 pump, the different power values described in this set of results are still comparable to each other, thus showing how the equipment used in this project provided results that were very similar to the theoretical information for the two different pump systems.

3.2.3 April 17, 2013

For the April 17, 2013 data set shown in Fig. 45, the average power consumption during the period that the heat exchanger was not in operation was 4.01 kW for the Worthington D-824 pump and 2.74 kW for the Grundfos CRE 15-3 pumps. Once the access valve of the heat exchanger was opened, those average power consumptions changed to 5.39 kW and 5.83 kW, respectively. The Grundfos CRE 15-3 pumps consumed much less energy (about 31.7% less) when compared to the Worthington D-824 pump during the period that the heat exchanger was out of action. However, when the heat exchanger was in operation, just like all the results in Case 2, the Grundfos CRE 15-3 pumps had higher (but still fairly similar) power consumption when compared to the Worthington D-824 pump.

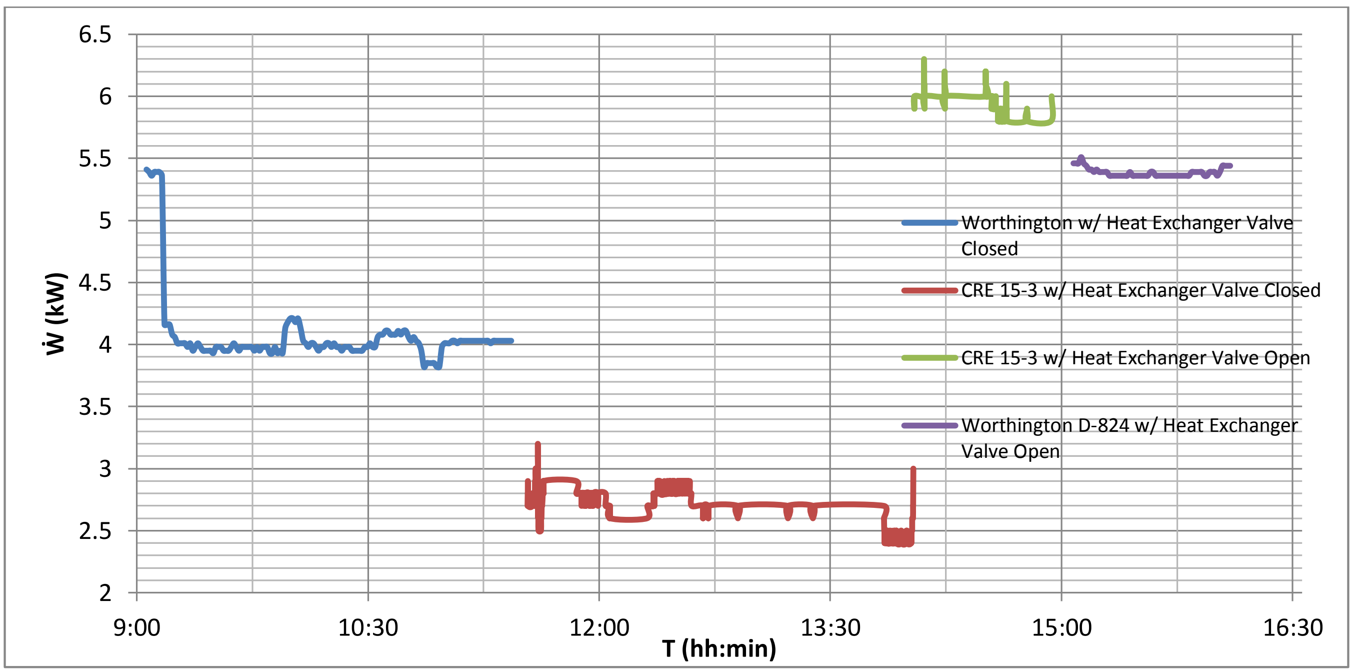


Figure 45: Grundfos CRE 15-3 vs. Worthington D-824 Power Consumption for April 17, 2013.

The corresponding flow rates for the power consumption on April 17, 2013 are shown in Fig. 46. The average flow rate for the period during which the heat exchanger did not have water supplied was 70.7 GPM for the Worthington D-824 pump and 76.6 GPM for the Grundfos CRE 15-3 pumps. Once the pumps were allowed to provide water to the heat exchanger, the average flow rates became 151.5 GPM (Worthington D-824) and 167.2 GPM (CRE 15-3).

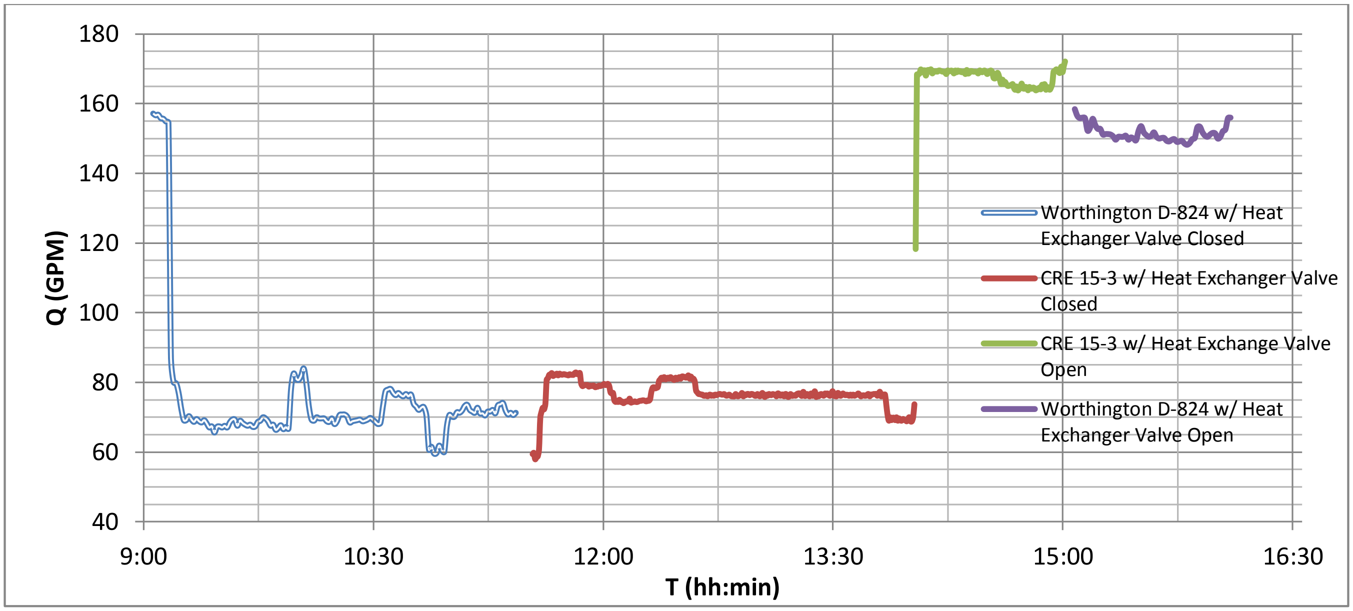


Figure 46: Grundfos CRE 15-3 vs. Worthington D-824 Flow Rate for April 17, 2013.

Looking at Fig. 47, one can see that, except for the period during which the Worthington D-824 pump ran with the heat exchanger access valve closed, both pump systems kept very similar discharge pressures during their hours of operation. When the heat exchanger access valve was closed, the Worthington D-824 pump had a 49.2 PSI average discharge pressure and the Grundfos CRE 15-3 pumps had a 43.0 PSI average discharge pressure. Once the access valve was opened, the CRE 15-3 pumps continued with a 43.0 PSI average discharge pressure, while the Worthington D-824 pump dropped its average discharge pressure to 42.98 PSI.

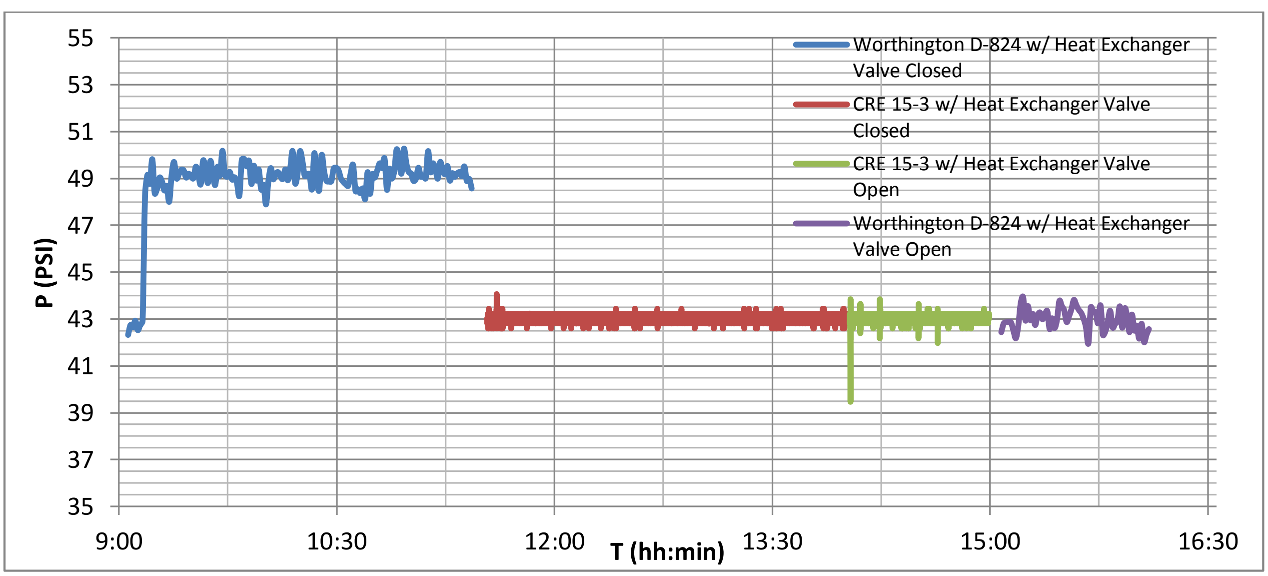


Figure 47: Grundfos CRE 15-3 vs. Worthington D-824 Discharge Pressure for April 17, 2013.

When the heat exchanger access valve was closed, using the pump curves, the theoretical power consumption found using the Grundfos' WEBCAPS [41] pump curve was 2.49 kW for the CRE 15-3 pump system, i.e., 9.12% lower than the recorded power (with a 58.9% pump and motor efficiency [41]), and 4.10 kW (5.5 HP) for the Worthington D-824 pump (35% pump efficiency), i.e., 2.24% higher than the recorded power (the higher value is again, assumed to be due to the lower pump efficiencies at lower flow rates and higher discharge pressure being used in Eq. (5)). For the period with the heat exchanger access valve open, the theoretical power for the CRE 15-3 pumps was 5.44 kW (6.69% lower than the recorded power with a 58.8% pump and motor efficiency [41]); and for the Worthington D-824 pump, it was 5.07 kW (5.94% lower than the recorded power with a 60% pump efficiency).

For the period when no water was supplied to the heat exchanger, the calculated average pump hydraulic power using Eq. (5) was 4.31 kW (5.79 HP) for the Worthington D-824 pump and 2.43 kW (3.26 HP) for the Grundfos CRE 15-3 pumps. The calculated power was just 7.48 % higher than the actual recorded power consumption for the Worthington D-824, while the calculated power for the CRE 15-3 was 11.3% lower than the recorded consumption value. Hence, these results show a reasonable consistency between calculated and measured values for the period during which the heat exchanger was not in operation.

Using the flow rate and discharge pressure values during which the heat exchanger was operational, Eq. (5)'s hydraulic power results were 4.72 kW (6.33 HP) for the Worthington pump and 5.31 kW (7.13 HP) for the Grundfos pumps. This time the calculated hydraulic power was 12.4% lower than the measured consumption for the Worthington D-824 pump, which could be due to the fact that the motor efficiency plays a bigger role in higher flow rates; however, this issue is not taken into consideration by the pump's curves. For this reason, even though these values were not too far apart from each other, in order to have the calculated average hydraulic power to be the same as the measured average power consumption, given the average flow rates and discharge pressure, the estimated combined motor and pump efficiency for the Worthington D-824 pump should have been approximately 52.5%. With respect to the Grundfos pumps, the calculated average hydraulic power was only 8.92% lower than the measured average power consumption. Therefore, this set of results shows how the recorded and theoretical values from both pump systems for this period of Case 2 are also consistent enough to establish a fair comparison between the power consumption values of these two pump systems.

3.2.4 April 18, 2013

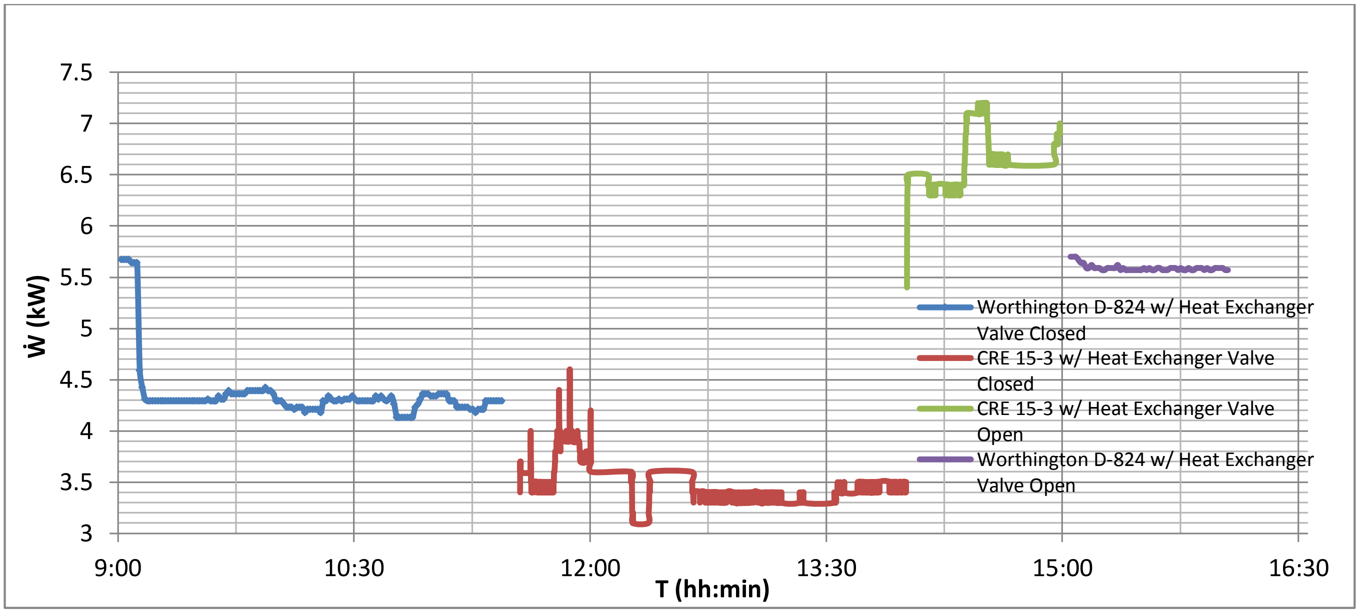


Figure 48: Grundfos CRE 15-3 vs. Worthington D-824 Power Consumption for April 18, 2013.

The variation in power consumption for seven hours on April 18, 2013 is shown in Fig. 48 (with the heat exchanger access valve closed). The average power consumption was 4.29 kW for the Worthington D-824 pump and 3.47 kW for the Grundfos CRE 15-3 pumps. When considering the time when the heat exchanger access valve was open, the Worthington D-824 had a 5.59 kW average power consumption while the CRE 15-3 pumps average was 6.63. Again, these results show that a lot more work was done by these pump systems when having to provide water to both the deaerator tank and the heat exchanger. (For data on the average ambient/environmental temperature for the periods discussed see Appendix D.)

As Fig. 49 shows, the Grundfos CRE 15-3 pumps had a higher flow rate for both periods of time, i.e., when the heat exchanger access valve was open and closed, as compared to the Worthington D-824 constant speed pump. However, the only period that it consumed more power was when the access valve was open. That could be due to the fact that variable speed pumps are normally more energy efficient when operating at lower flow rates as compared to constant speed pumps that are more energy efficient at higher flow rates [5]. The average flow rates for the period with the heat exchanger not operational was 86.2 GPM with an average 48.4 PSI discharge pressure (shown in Fig. 50) for the Worthington D-824 pump and 95.7 GPM with an average 43 PSI discharge pressure for the Grundfos CRE 15-3 pumps. Once the heat exchanger became operational, those average flow rates changed to 166.5 GPM at 41.4 PSI discharge for the Worthington pump and 184.8 GPM at 43.0 PSI discharge for the Grundfos pumps.

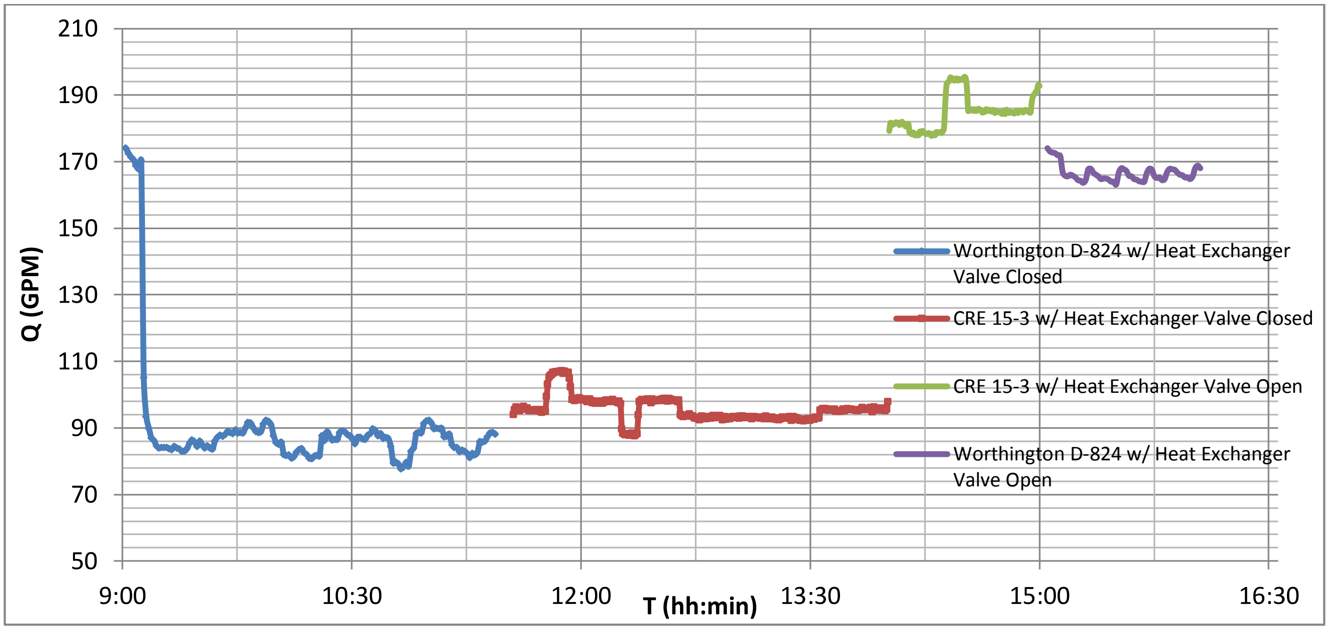


Figure 49: Grundfos CRE 15-3 vs. Worthington D-824 Flow Rate for April 18, 2013.

Using the average flow rates and discharge pressures from the pump curves of each pump system, when the heat exchanger access valve was closed, the theoretical power consumptions for the Worthington D-824 and Grundfos CRE 15-3 pumps were 4.25 kW (5.7 HP with an approximate 41% pump efficiency) and 3.16 kW (57.8% pump and motor efficiency), respectively. The Worthington D-824 pump's theoretical average consumption was 0.93% lower than the recorded power and the CRE 15-3 pumps' theoretical value was 8.93% lower than the recorded power consumption. Regarding the period when the heat exchanger access valve was open, the theoretical power consumption was 5.37 kW (7.2 HP with a 63% pump efficiency) for the Worthington D-824 pump and 6.05 kW (58.1% pump and motor efficiency) for the Grundfos CRE 15-3 pumps. These values were 3.93% (Worthington D-824) and 8.75% (Grundfos CRE 15-3) lower than the recorded power consumption values. Hence, these comparisons show how consistent the values obtained with the sensors used in this project were when compared to the theoretical values found in the pump curves of each system.

Using Eq. (5) to calculate the pump hydraulic power for the Grundfos CRE 15-3 pump system, the values obtained were 3.10 kW (4.153 HP) for the period with the heat exchanger access valve closed and 5.95 kW (7.98 HP) for the period during which water was supplied to the heat exchanger. These calculated values were 10.7% (access valve closed) and 10.3% (access valve open) lower than the recorded power consumption values. The Worthington D-824 pump's calculated hydraulic power was 4.42 kW (5.93 HP) for when the heat exchanger access valve was closed and 4.76 kW (6.38 HP) for the period with the access valve open. The calculated hydraulic power for the period with the access valve closed was 2.94% higher that the recorded power consumption; and, for the period with the access valve open, the hydraulic power was 28.2% lower than the recorded power consumption. This greater difference when the access valve was open could be due to the fact that the motor efficiency (not taken into consideration in the Worthington D-824 pump curves) plays a bigger role at higher flow rates. Thus, for the hydraulic power to be the same as the recorded power consumption, given the used average flow rate and discharge pressure, it is assumed the Worthington D-824 pump and motor efficiency should be approximately 45.2%.

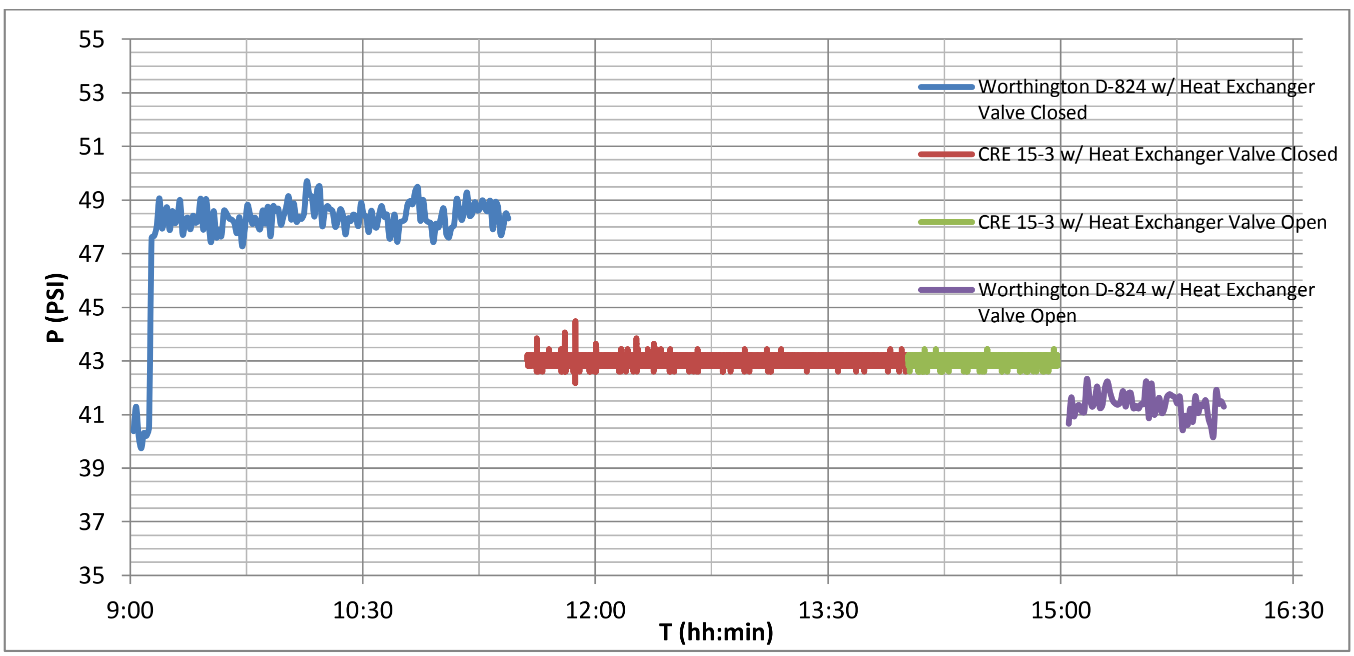


Figure 50: Grundfos CRE 15-3 vs. Worthington D-824 Discharge Pressure for April 18, 2013.

Figure 51 is another example of how the differential pressure across the control valve changed during the operation of the Worthington D-824 pump when the heat exchanger valve was open and closed. While the Worthington D-824 pump was in operation with the access valve closed, the average differential pressure was 34.25 PSI; and, when the access valve was open, the average differential pressure dropped to 27.34 PSI. This difference was due to the higher discharge pressure of the constant speed pump when the heat exchanger valve was closed. When observing the differential pressure, during the period that the Grundfos CRE 15-3 pumps were in operation, there was not much difference between the times when the heat exchanger valve was open and closed. The average differential pressure across the valve was 29.85 PSI when valve was closed and 27.09 PSI during the time that the valve was open. Again, this was due to the discharge pressure set-point of the CRE 15-3 pumps, so that they could increase or increase their speed in order to maintain the same discharge pressure based on the supply of water that the system needed.

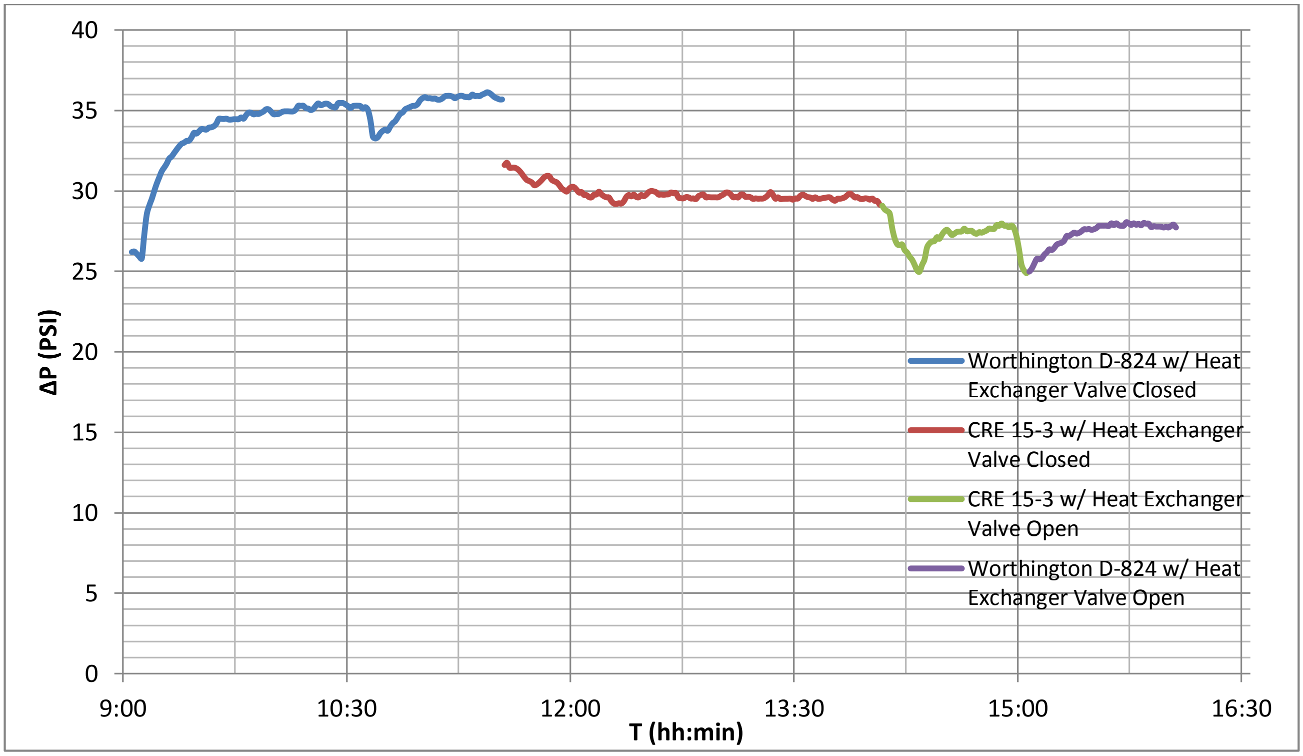


Figure 51: Grundfos CRE 15-3 vs. Worthington D-824 Differential Pressure across Control Valve for April 18, 2013

3.3 Case 3

3.3.1 April 30, 2013

For Case 3, the Grundfos CRE 15-3 pumps ran in level control mode with the control valve fully open, since it was the pump's speed that controlled the amount of water going into the deaerator tank. The Grundfos pumps' set point for its level control mode was 52%, i.e., the pumps tried to provide a supply of water to maintain that deaerator tank water level at approximately 52% of its capacity, a level that was established by the power plant's staff. When running the Worthington D-824 pump, the control valve still controlled the supply of water going into the deaerator tank, since this pump always worked in the discharge pressure mode. Each set of pumps ran for a period of approximately 3 hours each day for a total of two days with the heat exchanger access valve closed. This provided a fair comparison for the power consumption of each pump while the variable speed pumps ran in level control mode since, in this case, they were both just supplying water to the deaerator tank.

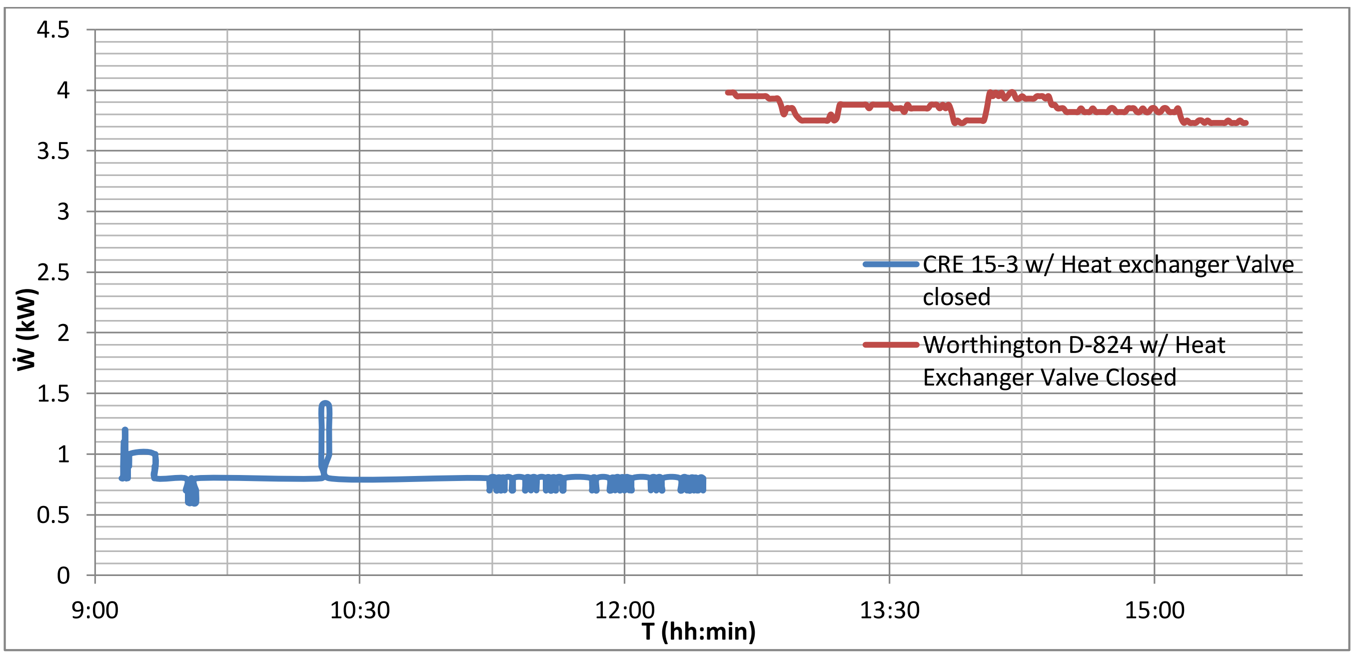


Figure 52: Grundfos CRE 15-3 vs. Worthington D-824 Power Consumption for April 30, 2013.

As Fig. 52 shows, when the heat exchanger access valve was closed and the Grundfos CRE 15-3 pumps ran in level control mode, they consumed a lot less power than the Worthington D-824 pumps. The average power consumption for the CRE 15-3 pumps was 0.80 kW while, for the Worthington D-824 pump, it was 3.84 kW. In terms of percentages, this means that, for approximately the same amount of operating time, the Grundfos pumps consumed about 79.2% less energy than the Worthington pump.

When looking at the flow rates in Fig. 53, both sets of pumps seemed to have provided fairly similar flow rates. However, Fig. 54 shows how the constant speed centrifugal pump discharge pressure was much higher than that of the variable speed pumps. That difference in pressure was due to the fact that the control valve was fully open when the Grundfos pumps were in operation, and while the Worthington pump was running, the control valve was in operation in order to manage the water supplied to the deaerator tank. The average flow rate for the Worthington D-824 pump was approximately 56.7 GPM with a 49.7 PSI discharge pressure, and the Grundfos CRE 15-3 pumps' average flow rate was 56.1 GPM with a 13.1 PSI discharge pressure.

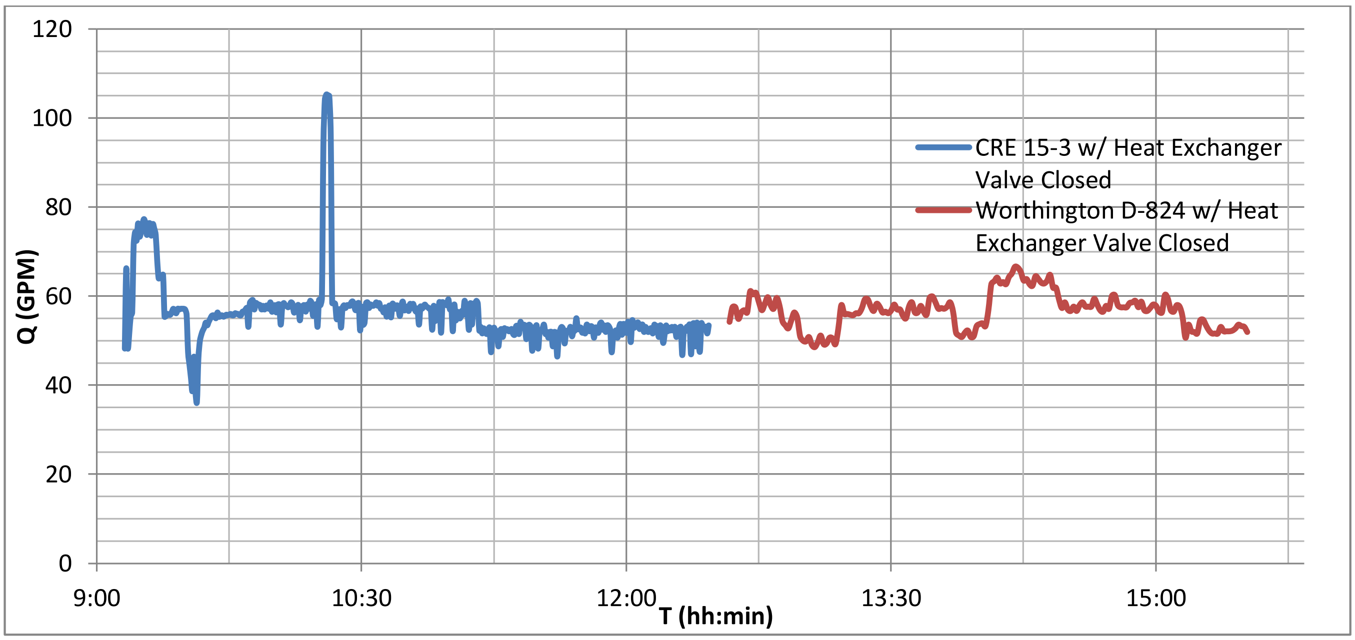


Figure 53: Grundfos CRE 15-3 vs. Worthington D-824 Flow Rate for April 30, 2013.

When plotting the average flow rate and discharge pressure values using the Grundfos CRE 15-3 WEBCAPS pump curve information, the theoretical power obtained was 0.687 kW with a pump and motor efficiency of 47.5% [41]. Following the same procedure with the averages for the Worthington D-824 pump, the estimated theoretical power obtained was 3.80 kW (5.1 HP) with an approximate 30% pump efficiency. For the Grundfos CRE 15-3 pumps, the theoretical power was about 14.1% lower than the recorded power, while for the Worthington D-824 pump, the theoretical power was 1.04% lower than the recorded power. The difference between the theoretical and recorded power values for the Grundfos pumps seem high when compared to the Worthington D-824 numbers, due to the fact that the values being dealt with are so small that minor differences such as 0.15 kW lead to higher percentage differences. However, the recorded power consumption values can still be considered comparable to the theoretical values found in the pump curves.

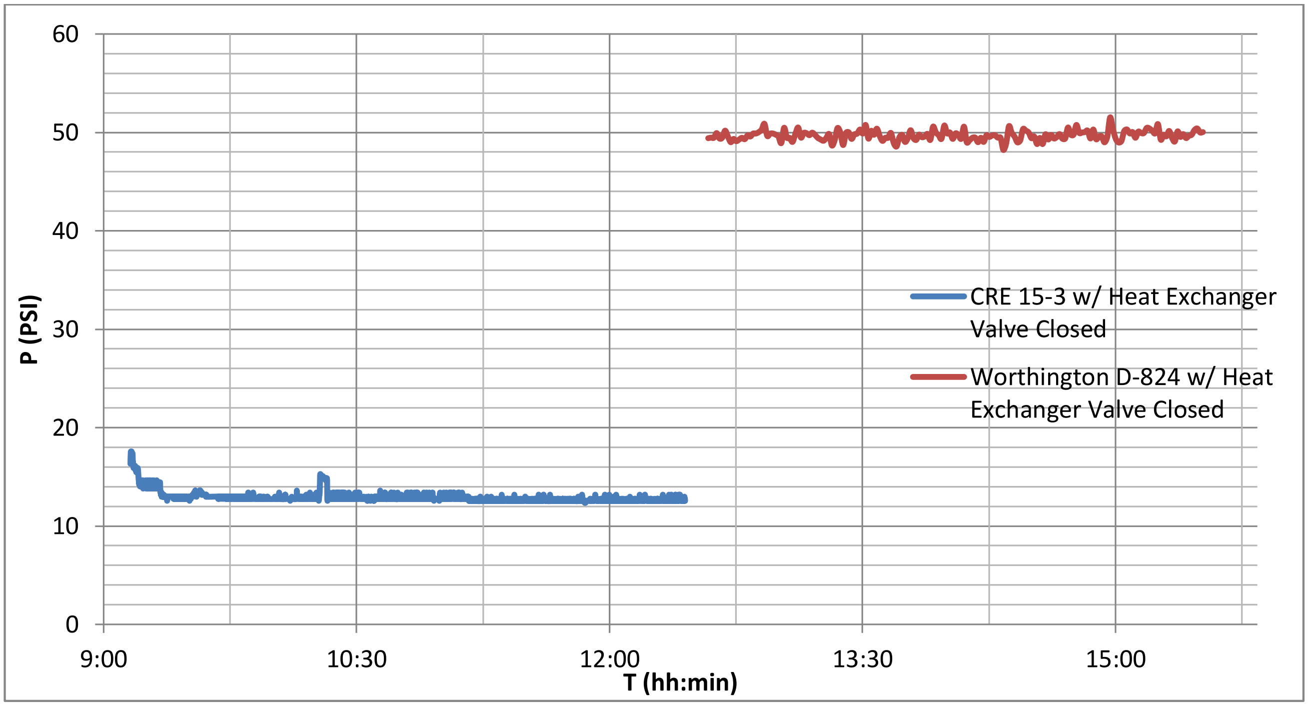


Figure 54: Grundfos CRE 15-3 vs. Worthington D-824 Discharge Pressure for April 30, 2013.

The calculated average hydraulic power using Eq. (5) for the Grundfos CRE 15-3 pumps was 0.673 kW (0.903 HP), being 15.9% lower than the recorded power consumption. With respect to the Worthington D-824 pump, the calculated average hydraulic power was 4.08 kW (5.48 HP), 6.25% higher than the recorded power consumption. (Again, it was assumed that the calculated hydraulic power was higher than the recorded value due to the lower pump efficiency at lower flow rates as well as the higher discharge pressure used in Eq. (5).) Even though the theoretical and calculated data have a higher difference from the recorded data when compared to the results of previous cases, this set of values still shows that less power was consumed by the variable speed pumps in level control mode as compared to the Worthington D-824 power consumption when the two pump systems were only supplying water to the deaerator tank.

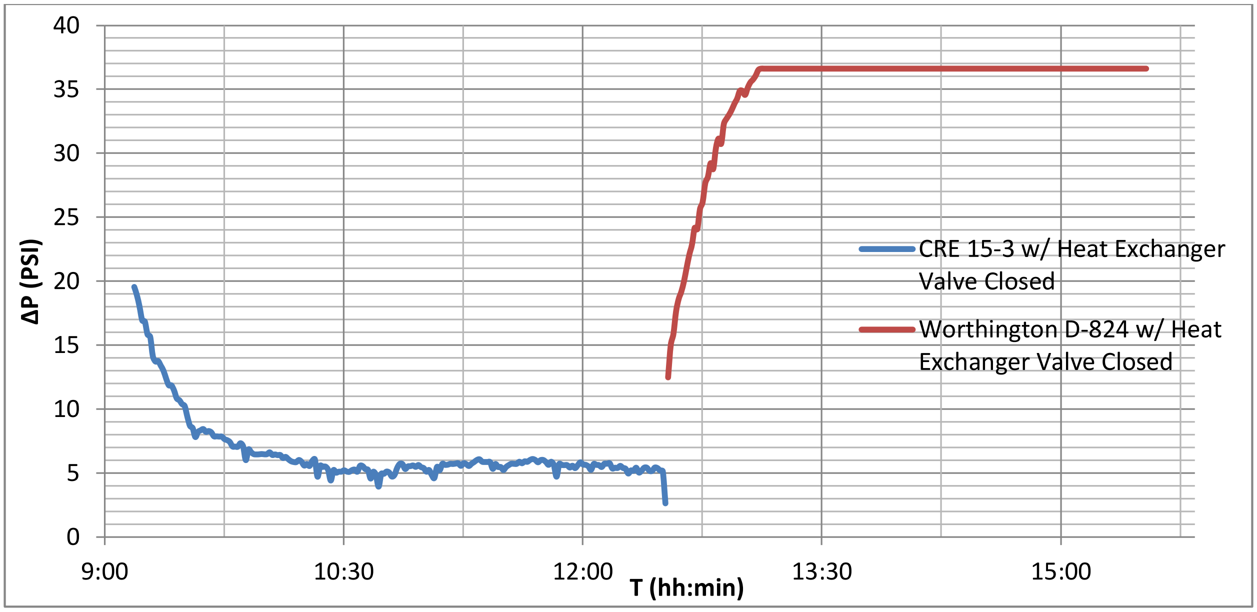


Figure 55: Grundfos CRE 15-3 vs. Worthington D-824 Differential Pressure across Control Valve for April 30, 2013

Figure 55 shows the differential pressure across the control valve when the heat exchanger valve was closed and the Grundfos CRE 15-3 pumps were running in level control mode, as compared to the Worthington D-824 pump results. Whenever the Grundfos CRE 15-3 pumps ran in level control mode, the control valve was manually set to be fully open. For this reason, Fig. 55 shows how the differential pressure across the valve was so low during the time the CRE 15-3 pumps were in operation. The average differential pressure across the valve when the CRE 15-3 pumps were running was 6.64 PSI. Even though the pressure was expected to be very close to zero once the valve was fully open, the valve still provided a small pressure drop in the system.

The initial part of the blue line with the negative slope represents the amount of time it took the pneumatic system that controls the valve to completely get rid of the air that controls the opening and closing of the valve. The same idea follows for the initial part of the red line with a positive slope, which represents the pneumatic system slowly providing air back to the control valve until it was fully operational. The average differential pressure across the valve when the Worthington D-824 pump was in operation was 34.91 PSI, which is very close to the differential pressure measured in Case 2. Hence this shows how the control valve played a minor role when the CRE 15-3 pumps ran in level control mode.

3.3.2 May 1, 2013

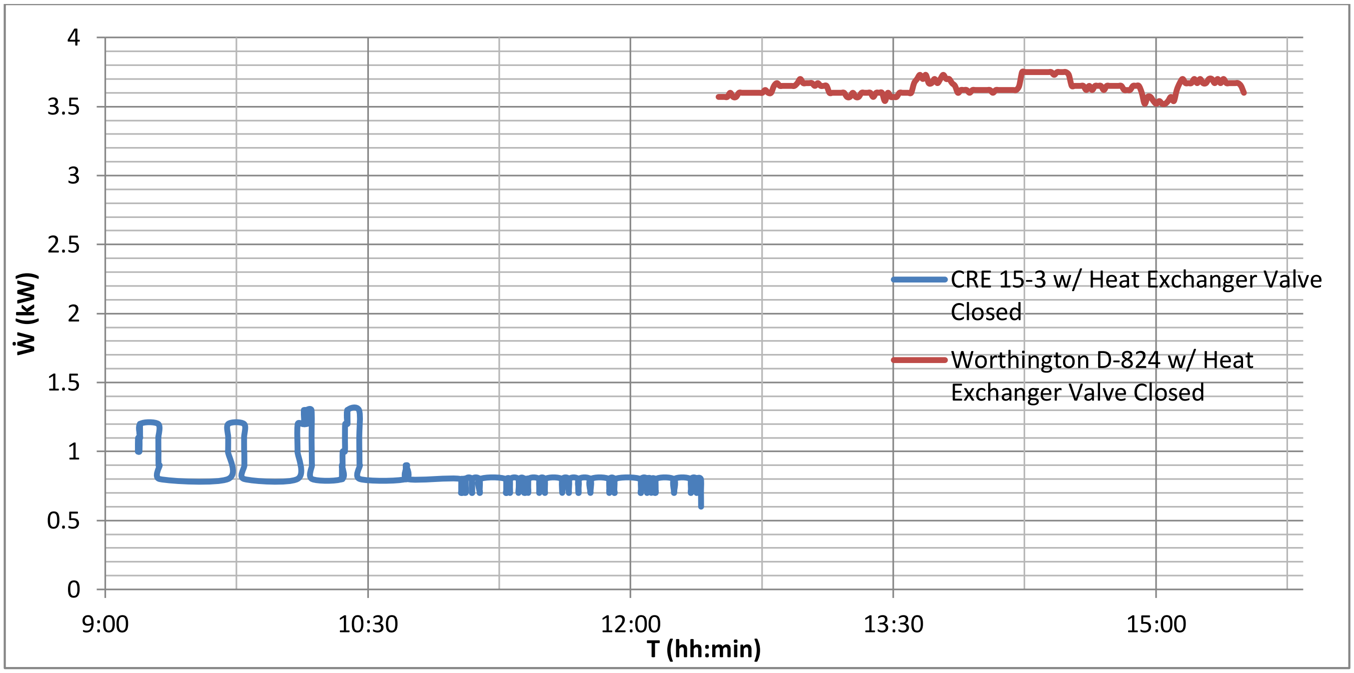


Figure 56: Grundfos CRE 15-3 vs. Worthington D-824 Power Consumption for May 1, 2013.

For the data shown in Fig. 56, the average power consumption of the Grundfos CRE 15-3 pumps was 0.876 kW, while the average power consumption for the Worthington D-824 pump was 3.64 kW.

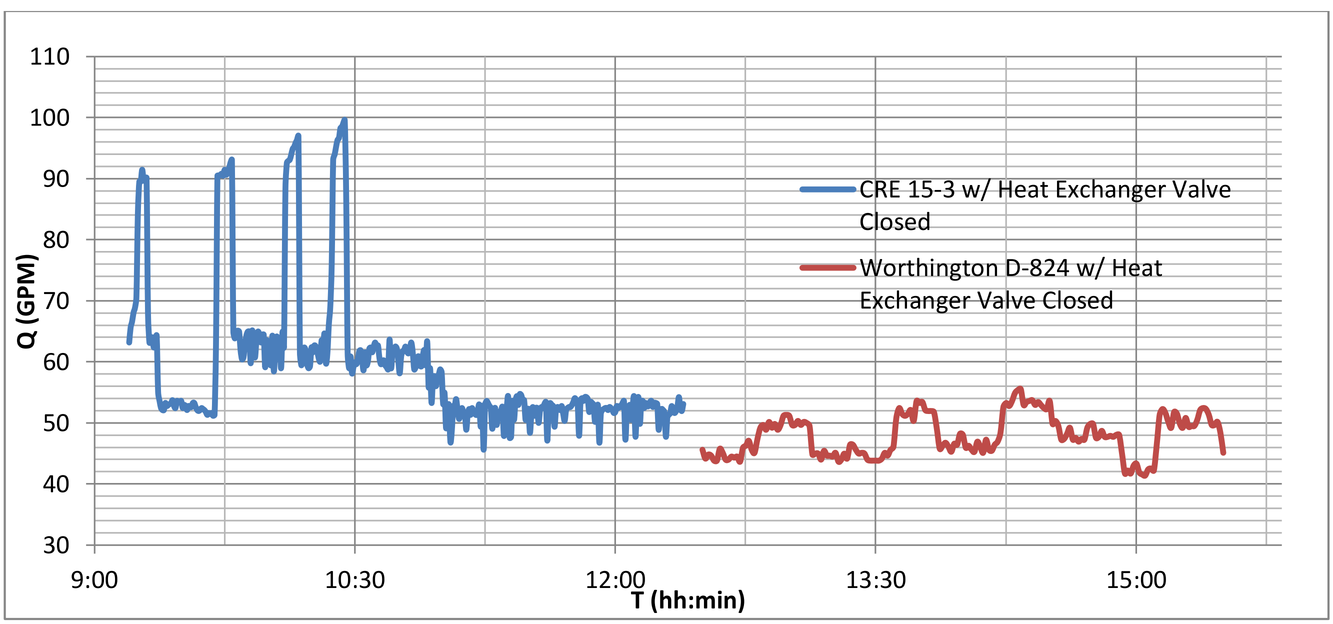


Figure 57: Grundfos CRE 15-3 vs. Worthington D-824 Flow Rate for May 1, 2013.

The four large peaks present in the period between 9:00 and 10:30 in both Figs. 56 and 57 represent a time during which the level of the deaerator tank dropped below the set point of 52% water capacity and the pumps had to increase the flow rate (and consequently power consumption) to reach the chosen set point. The rapid increases in flow rates were manually adjusted by this researcher in attempt to bring the level of water back to the desired set-point, since the previously used lower flow rates were not enough to maintain the set-point. However, as one can see in Fig. 58, the discharge pressure of the Grundfos pumps was not significantly affected by those large changes in flow rate. Having that explained, the average flow rate for the Grundfos CRE 15-3 pumps was 59.7 GPM with a 13.3 PSI average discharge pressure; and the Worthington D-824 pump had a 47.9 GPM average flow rate with an average 49.9 PSI discharge pressure.

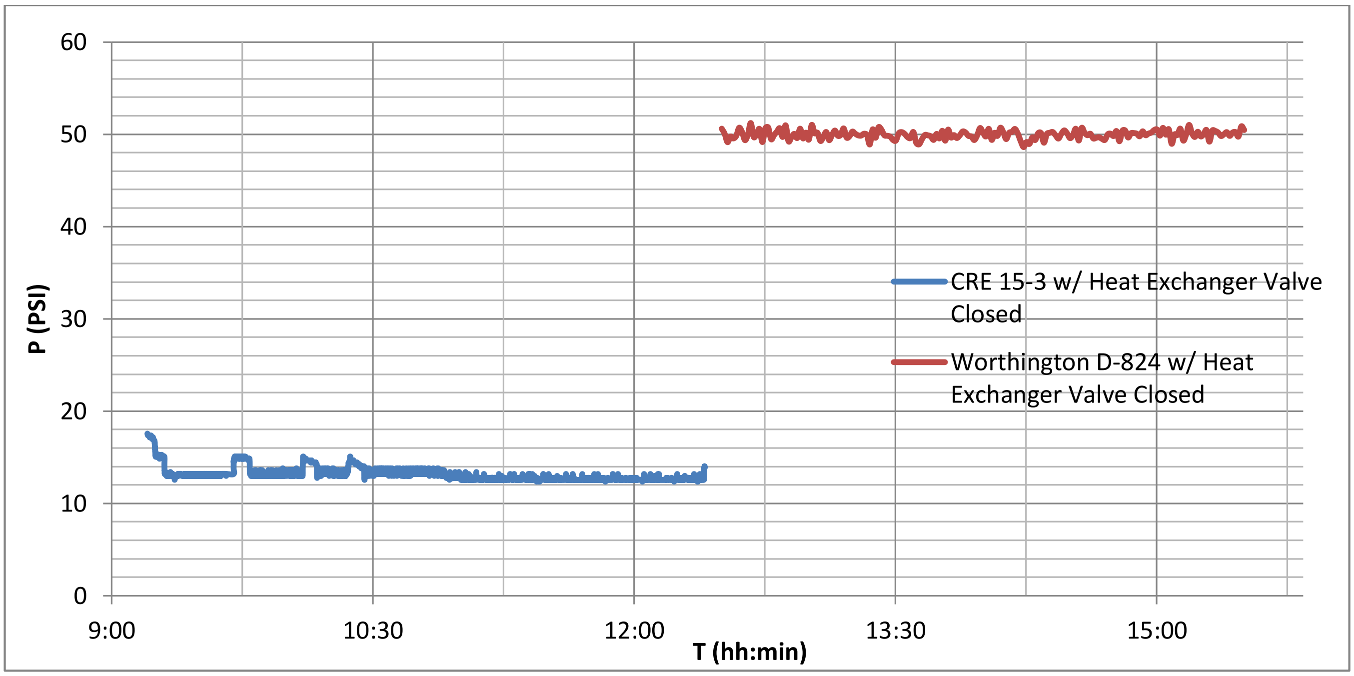


Figure 58: Grundfos CRE 15-3 vs. Worthington D-824 Discharge Pressure for May 1, 2013.

The Grundfos CRE 15-3 pumps’ average theoretical power obtained from the WEBCAPS pump curve, based on the average flow rate and discharge pressure, was 0.746 kW (with a 47.3% pump and motor efficiency [41]), about 14.8% lower than the recorded power consumption. Using Eq. (5) the calculated average hydraulic power was 0.730 kW (0.979 HP), 16.6% lower than the recorded power consumption. The Worthington D-824 theoretical power was 3.73 kW (25% pump efficiency), 2.47% higher than the average recorded power consumption. The calculated average hydraulic power for this pump was 4.16 kW (5.575 HP), 14.3% higher than the recorded power consumption. Hence, these values still show that, when these two sets of pumps just supplied water to the deaerator tank, the Grundfos CRE 15-3 pumps consumed considerably less power than the Worthington D-824 pump when the Grundfos pumps ran in level control mode rather than discharge pressure mode. However, by having the heat exchanger valve closed, one is not considering the amount of steam that is being lost into the air instead of being reused by the power plant as condensed water, which in the long run could increase the plant's water costs.

3.4 Case 4

3.4.1 March 11, 2013

The next series of results was obtained following the procedures for Case 4 explained in Section 2.3. The Grundfos CRE 15-3 pumps ran in level control mode with the control valve by the deaerator tank fully opened, while the Worthington D-824 constant speed pump still worked together with the control valve to limit the flow of water going into the deaerator tank. Each pump ran for a total of approximately five hours every day for a total of ten days (data of only 3 days is show in this section). This information was gathered before realizing that the variable speed pumps were not able to provide water to the heat exchanger on the first floor of the power plant due to their low discharge pressure when running in level control mode (as the dates shown in this section predate the results obtained for Case 3). Since the Worthington D-824 pump was still supplying water to both the deaerator tank and the heat exchanger, while the Grundfos CRE 15-3 pumps were just supplying water to the deaerator tank, this set of results are not a fair comparison of power consumption values to be used in a life cycle cost analysis between these two sets of pumps. However, based on the results from Case 2, very rough estimates can be made to approximate the power consumption and flow rates in Case 4 if the heat exchanger were excluded.

Between having the heat exchanger access valve closed and open, based on all the dates that data was gathered for the Worthington D-824 pump in Case 2, the average difference in flow rate was 80 GPM lower whenever the access valve was closed with an average 6.63 PSI higher discharge pressure. Also, comparing the power consumption values, every time the heat exchanger valve was closed, the Worthington D-824 pump consumed an average 1.35 kW less power than when the access valve was open. Since this average was consistent for all of the data recorded in Case

2, in order to have rough estimates for Case 4 when comparing Grundfos CRE 15-3 and Worthington D-824 pumps' power consumption and flow rates, 1.35 kW and 80 GPM were deducted from the average power consumption and flow rates, respectively, while increasing 6.63 PSI in the average discharge pressure. Again, these very rough estimates have been made as an attempt to fairly compare the two sets of pumps by trying to exclude the heat exchanger from the work done by the Worthington D-824 pump.

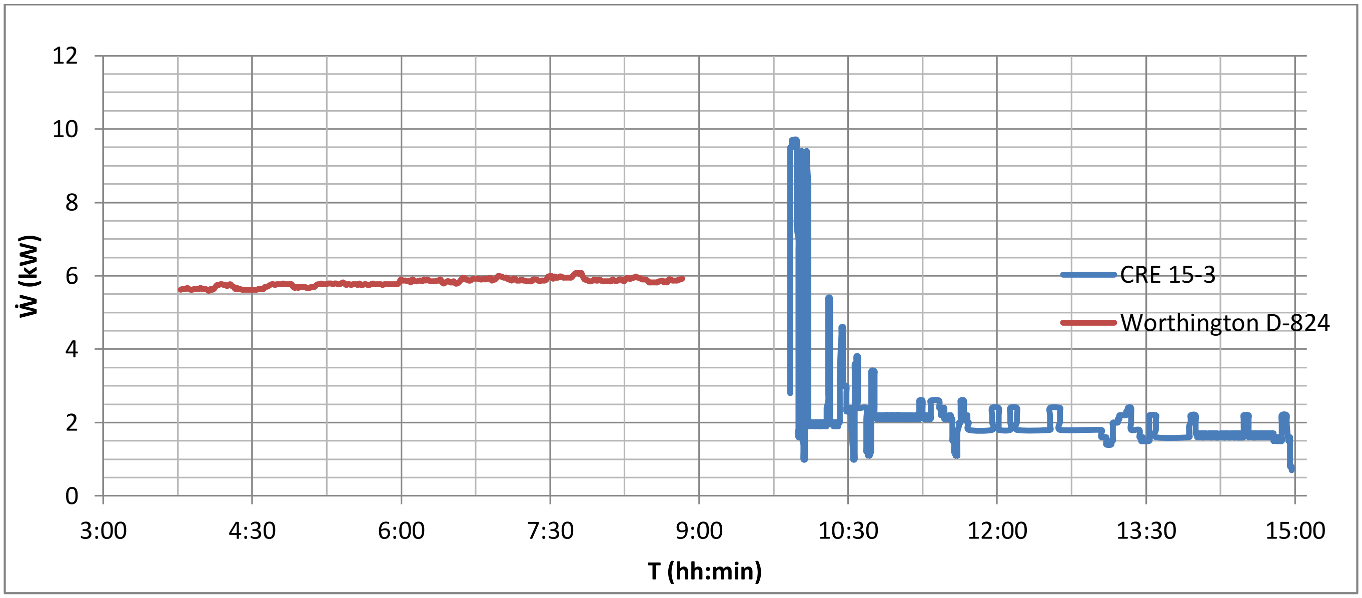


Figure 59: Grundfos CRE 15-3 vs. Worthington D-824 Power Consumption for March 11, 2013.

Based on the information presented in Fig. 59, the average power consumption for the Worthington D-824 pump during March 11, 2013 was 5.82 kW. However, by using estimates from Case 2, and subtracting 1.35 kW from that value, this should represent a rough approximation of the constant speed pump's power consumption if the heat exchanger was taken out of consideration. So the average power consumption for the Worthington D-824 pump would be 4.47 kW. However, no matter what power consumption from the Worthington D-824 pump that the Grundfos results are compared to, the Grundfos power consumption is still significantly smaller by running in level control mode.

The curve representing the power consumption of the Grundfos CRE 15-3 pumps show large changes in power consumption in the beginning, and, as time passed, the curve became fairly damped. This is present in the graph, showing the damping that was manually performed by this author using the R100 remote control. This was done by simultaneously changing the minimum and maximum speeds that the pumps could reach until a small difference between minimum and maximum allowable speeds was reached based on the demand of water necessary to keep the level of the deaerator tank at the desired set point; increasing or decreasing these minimum and maximum speed boundaries depending how the demand of the power plant changed throughout the day. This is the kind of damping that the pumps' controller was expected to perform automatically; but unfortunately damping had to be manually performed by this author.

Having that explained, the Grundfos CRE 15-3 pumps' average power consumption was 2.14 kW. This shows how both pumps for this period consumed more power than when compared to the periods shown for Case 3. This was due to the colder weather during the days data was gathered for Case 4. (For data on the average temperature for the periods discussed, see Appendix D.)

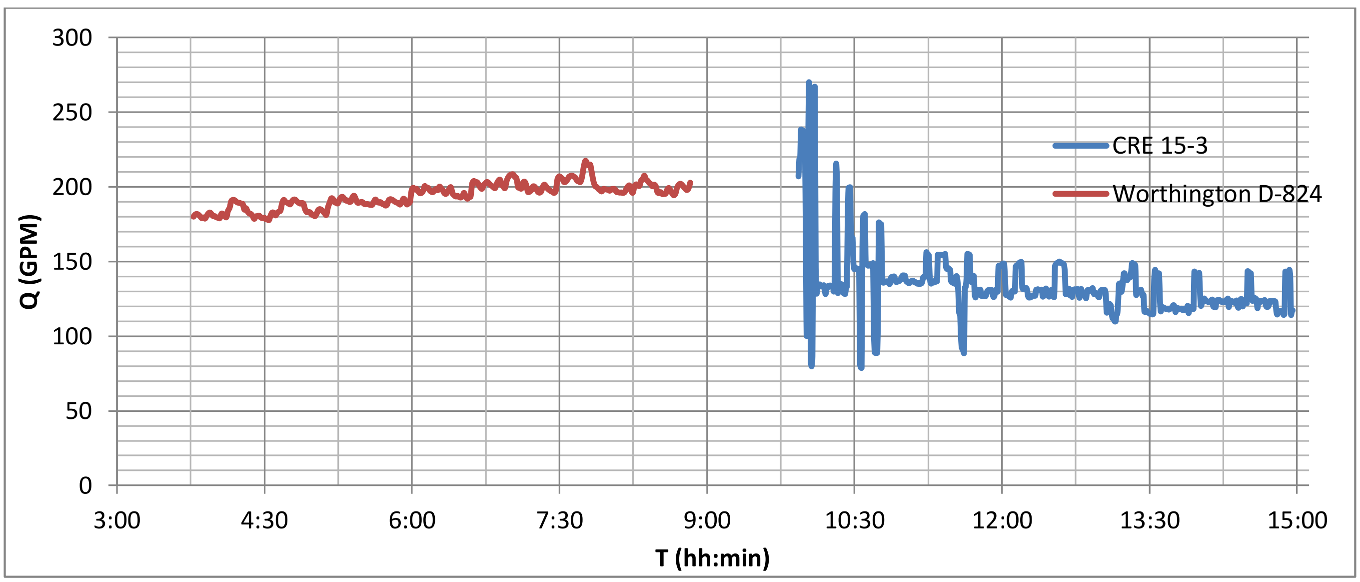


Figure 60: Grundfos CRE 15-3 vs. Worthington D-824 Flow Rate for March 11, 2013.

The average flow rate for the Worthington D-824 pump, based on the data shown in Fig. 60, was 194.1 GPM, while the average flow rate for the Grundfos CRE 15-3 pumps was 134.3 GPM. Again, these higher flow rates suggest that the power plant's demand was higher than in the previous cases, so the subtraction of 80 GPM from the constant speed pump flow rate (to attempt to remove the extra work done for the heat exchanger) is a very rough estimate, since a part of that could be going into the deaerator tank due to the higher demand. By "excluding" the heat exchanger, the Worthington D-824 pump's average flow rate would be approximately 114.1

GPM if 80 GPM was subtracted from the average recorded flow. From Fig. 61, the average discharge pressure for the Worthington D-824 pump was 38.4 PSI (estimated to be 45 PSI if excluding the heat exchanger by adding 6.63 PSI), and an average of 16.8 PSI for the Grundfos CRE 15-3 pumps.

When plotting the average flow rate and discharge pressure of the Grundfos CRE 15-3 pumps on their pump curve, the theoretical power obtained was 2.02 kW (with a 49.7% pump and motor efficiency [41]), which is 5.6% lower than the recorded power consumption. The theoretical power consumption for the Worthington D-824 when using the actual average flow rate and discharge pressure was 5.66 kW (68% pump efficiency), about 2.75% lower than the recorded power. When using the altered flow rate and discharge pressure, the theoretical power was 4.70 kW (50% pump efficiency), about 5.15% higher than the estimated power consumption.

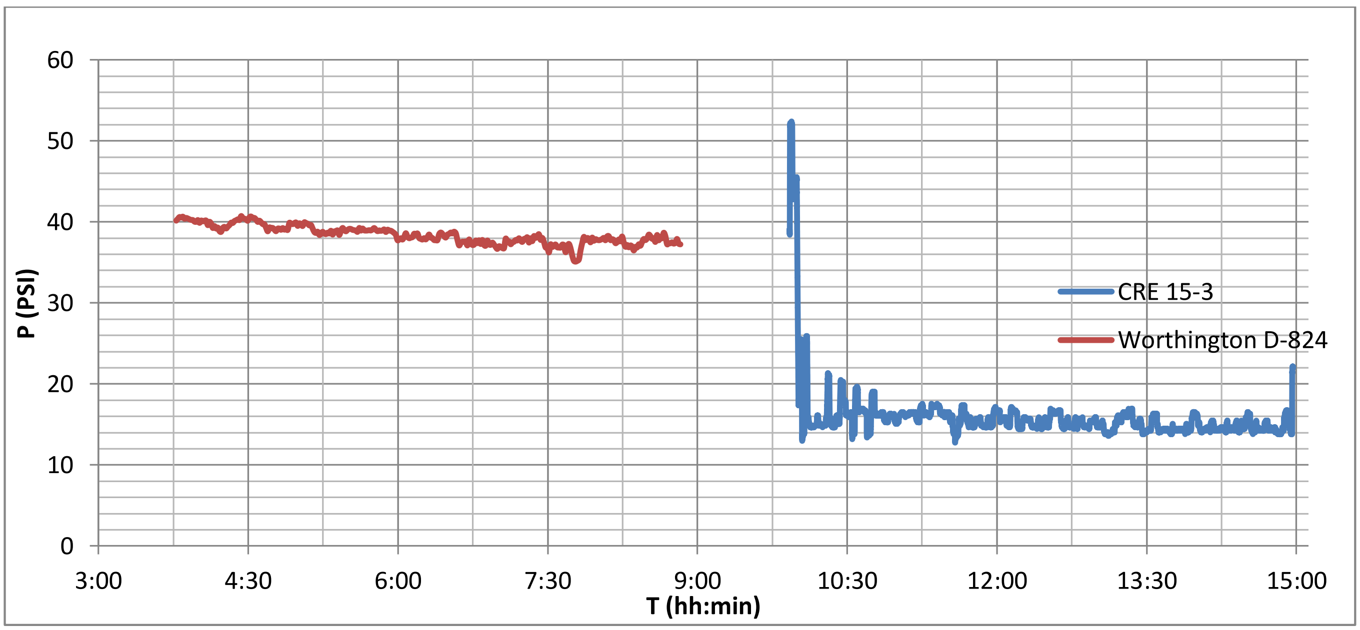


Figure 61: Grundfos CRE 15-3 vs. Worthington D-824 Discharge Pressure for March 11, 2013.

The Grundfos CRE 15-3 pumps' calculated average hydraulic power (using Eq. (5)) was 1.97 kW (2.64 HP), 7.94% lower than the recorded power consumption. With respect to the Worthington D-824 pump, the average hydraulic power was 4.77 kW (6.39 HP) when using the actual recorded values, which is about 18% lower than the average recorded power consumption. This means that, for the calculated average hydraulic power to be the same as the recorded power, the motor and pump combined efficiency should be approximately 55.7% instead of 68%.

When using the estimated flow rate and discharge pressure, the calculated average hydraulic power was 4.46 kW (5.99 HP), which was within 7.62% of the modified recorded power consumption. Hence, after accounting for the heat exchanger's requirements, recorded values for this set of results have differences from the pumps' theoretical values which are similar to those seen in Cases 1 through 3.

3.4.2 March 19, 2013

Based on the information for the period shown in Fig. 62, the average power consumption for the Grundfos CRE 15-3 variable speed pumps was approximately 1.44 kW, while the Worthington D-824 constant speed pump's average power consumption was 5.47 kW. Once the power that was assumed to be required to supply water to the heat exchanger was removed (about 1.35 kW), the estimated average power consumption became 4.12 kW.

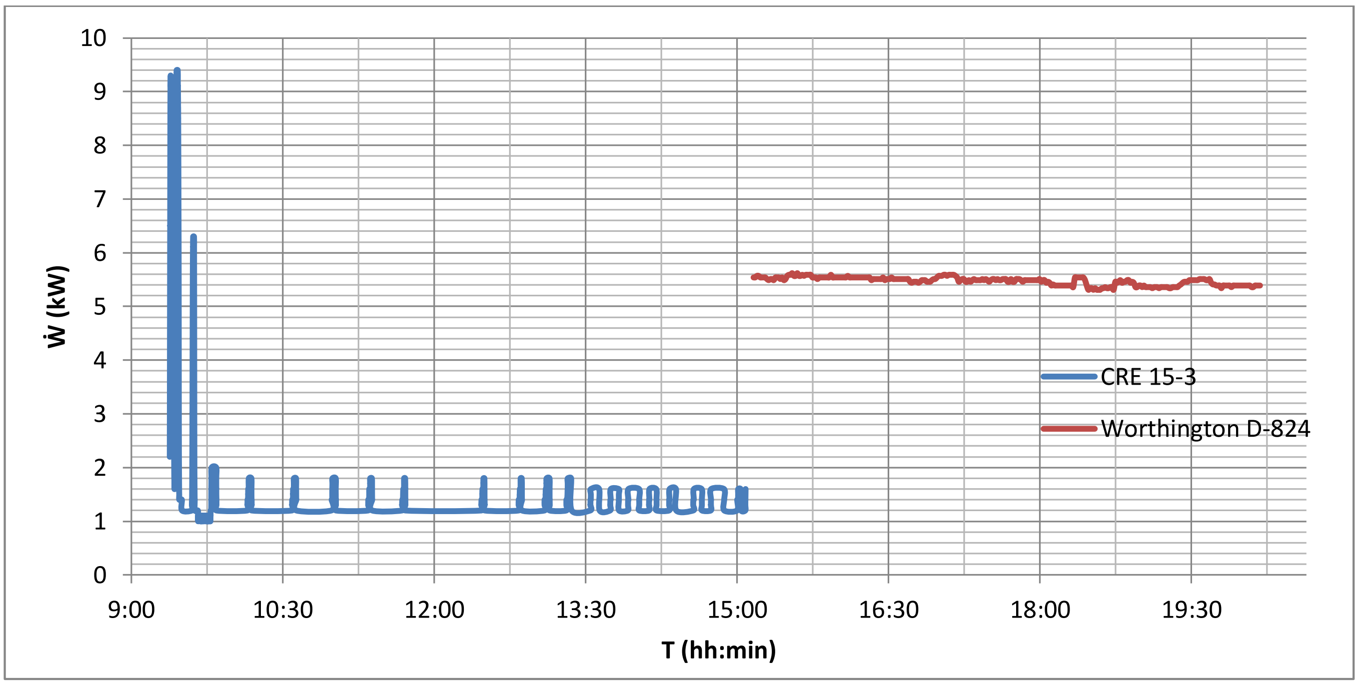


Figure 62: Grundfos CRE 15-3 vs. Worthington D-824 Power Consumption for March 19, 2013.

The average flow rate for the Grundfos CRE 15-3 pumps during the period shown in Fig. 63 was 96.4 GPM, and the average recorded discharge pressure for the data presented in Fig. 64 for this set of pumps was 15.6 PSI. The Worthington D-824 pump's average recorded flow rate and discharge pressure were 158.4 GPM and 41.8 PSI, respectively. The average estimated flow rates and discharge pressure, i.e., the values that were estimated if the constant speed pump was just supplying water to the deaerator tank, were 78.4 GPM and 48.4 PSI.

The Grundfos CRE 15-3 pumps' theoretical average power was 1.34 kW (49.9% pump and motor efficiency), which is 6.94% lower than the average recorded value. The theoretical power consumption for the Worthington D-824 pump using the average recorded values was 5.29 kW (62% pump efficiency), approximately 3.29% lower than the recorded value; and when using the estimated values obtained by not considering the heat exchanger while the Worthington D-824 pump was running, the calculated theoretical power was 4.17 kW (38% pump efficiency), approximately 1.21% higher than the estimated 4.12 kW power consumption obtained from measurements.

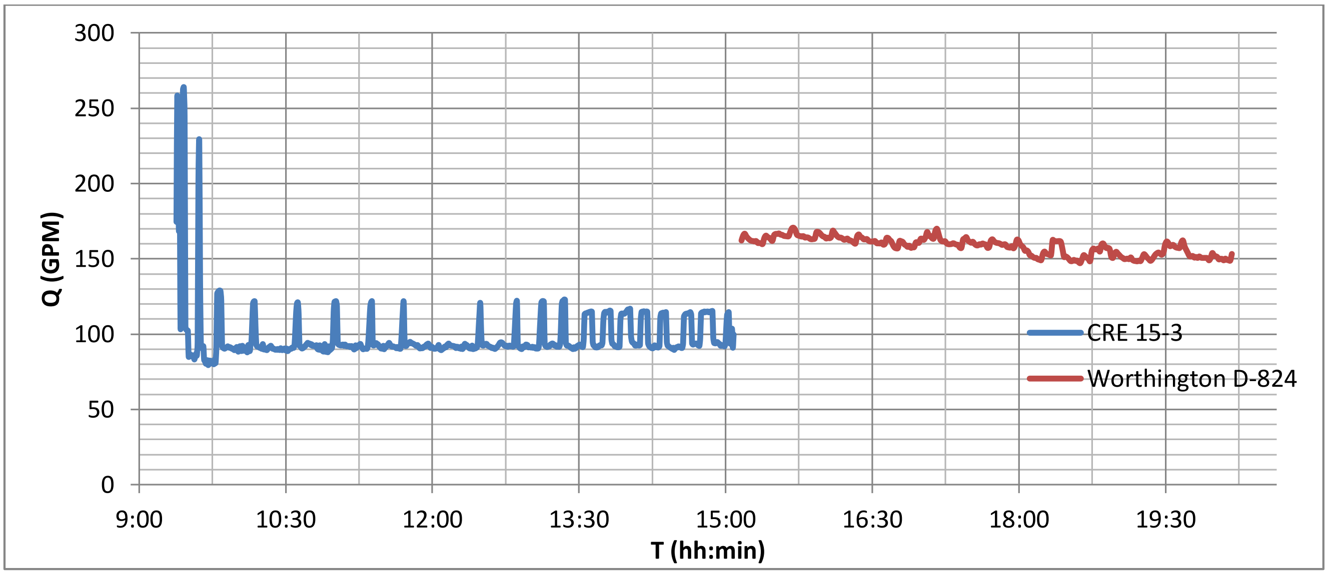


Figure 63: Grundfos CRE 15-3 vs. Worthington D-824 Flow Rate for March 19, 2013.

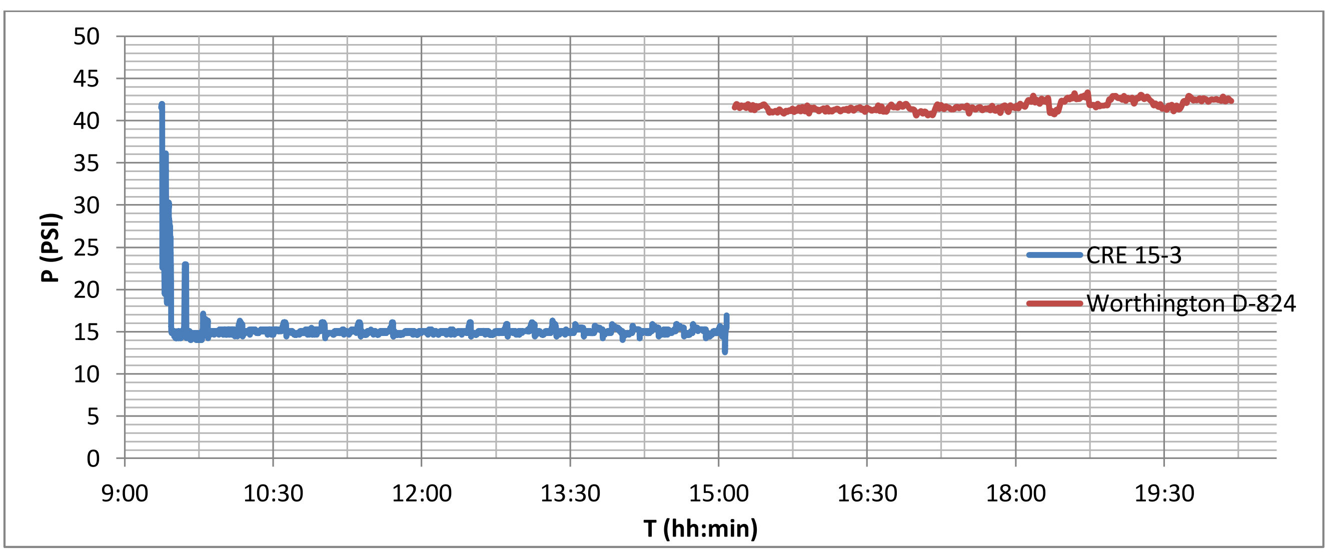


Figure 64: Grundfos CRE 15-3 vs. Worthington D-824 Discharge Pressure for March 19, 2013.

Using Eq. (5), the average calculated hydraulic power obtained for the Grundfos CRE 15-3 pumps was approximately 1.30 kW (1.75 HP), about 9.72% lower than the recorded power consumption. The average calculated hydraulic power for the Worthington D-824 pump was approximately 4.65 kW (6.23 HP) when using the average recorded flow rate and discharge pressure (about 15% lower than the recorded power consumption); and 4.30 kW (5.77 HP) when using the estimated flow rate and discharge pressure (about 4.37% higher than the estimated power consumption).

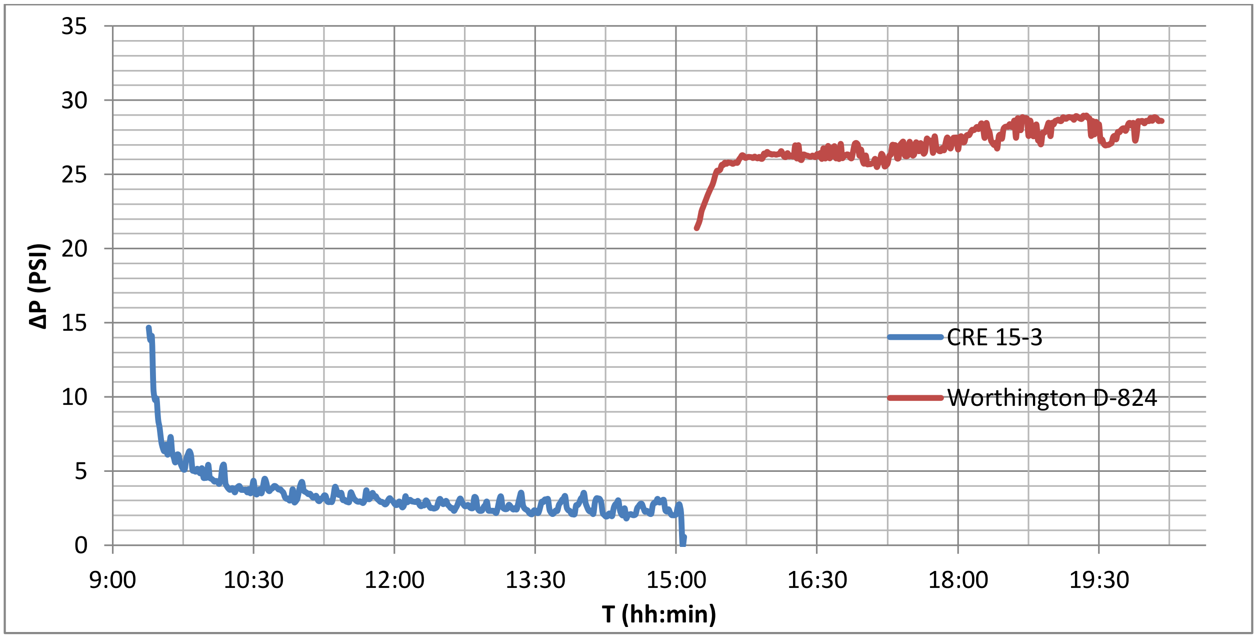


Figure 65: Grundfos CRE 15-3 vs. Worthington D-824 Differential Pressure across Control Valve for March 19, 2013

Based on the data shown in Fig. 65, when operating the Grundfos CRE 15-3 pumps in level control mode with the control valve fully open, the average differential pressure across the valve was 3.37 PSI. This just shows how the control valve did not play a major role in controlling the supply of water that the CRE 15-3 pumps provided to the deaerator tank. This is because the CRE 15-3 pumps were increasing and decreasing the flow based on the level of water in the deaerator tank. Hence, this shows that a control valve is not necessary when the Grundfos pump is supplying water to the system in level control mode. However, as observed in Fig. 64, due to the CRE 15-3 pumps' low discharge pressure when supplying this flow, they could only supply water to the deaerator tank and not the heat exchanger. On the other hand, once the Worthington D-824 pump was in operation and the control valve was turned on, the average differential pressure was 27 PSI, controlling the supply of water going into the deaerator tank and also allowing water to be provided to the heat exchanger. Hence, these figures and values show that, even though the Grundfos CRE 15-3 pumps consumed less energy to supply water to the system, while in level control mode, they could not supply water to the heat exchanger like the Worthington D-824 pump.

3.4.3 April 2, 2013

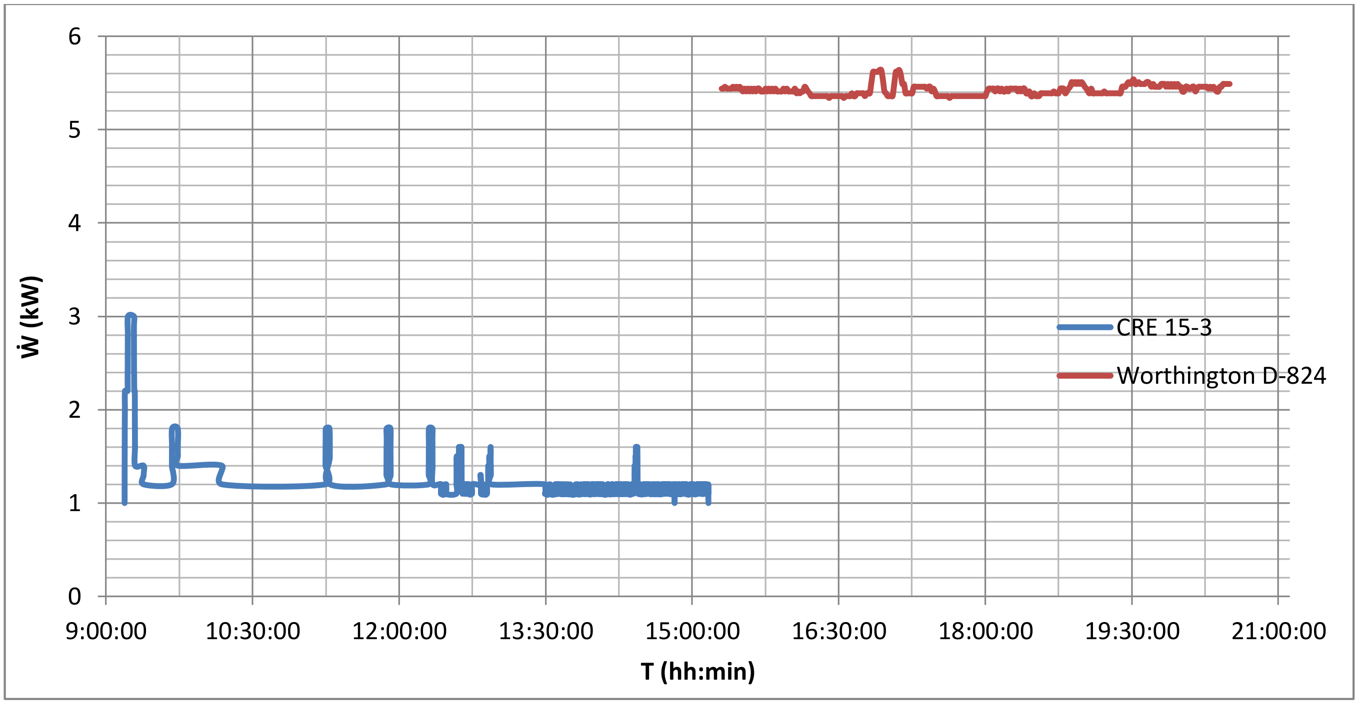


Figure 66: Grundfos CRE 15-3 vs. Worthington D-824 Power Consumption for April 2, 2013.

Given the data presented in Fig. 66, the average power consumption for the approximate five hour period that the Grundfos CRE 15-3 pumps ran was about 1.22 kW, while the average power consumption for the Worthington D-824 pump was about 5.43 kW. By using the same reduction as applied to the previous two sets of results, it is estimated that the power consumption for the Worthington D-824 pump would have been 4.08 kW, if no water was being supplied to the heat exchanger.

For the Grundfos CRE 15-3 pumps' flow rate data shown in Fig. 67, the average was 89.4 GPM, and the Worthington D-824 pump's average flow rate was 155.9 GPM. The estimate for the flow rate if the Worthington D-824 pump was not supplying water to the heat exchanger would be approximately 75.9 GPM. The average discharge pressures for the Grundfos CRE 15-3 pumps and the Worthington D-824 pump obtained for the data presented in Fig. 68 were 14.9 PSI and 42.5 PSI, respectively. Again, assuming no water was supplied to the heat exchanger while the Worthington D-824 pump operated, the estimated discharge pressure would have been approximately 49.13 PSI.

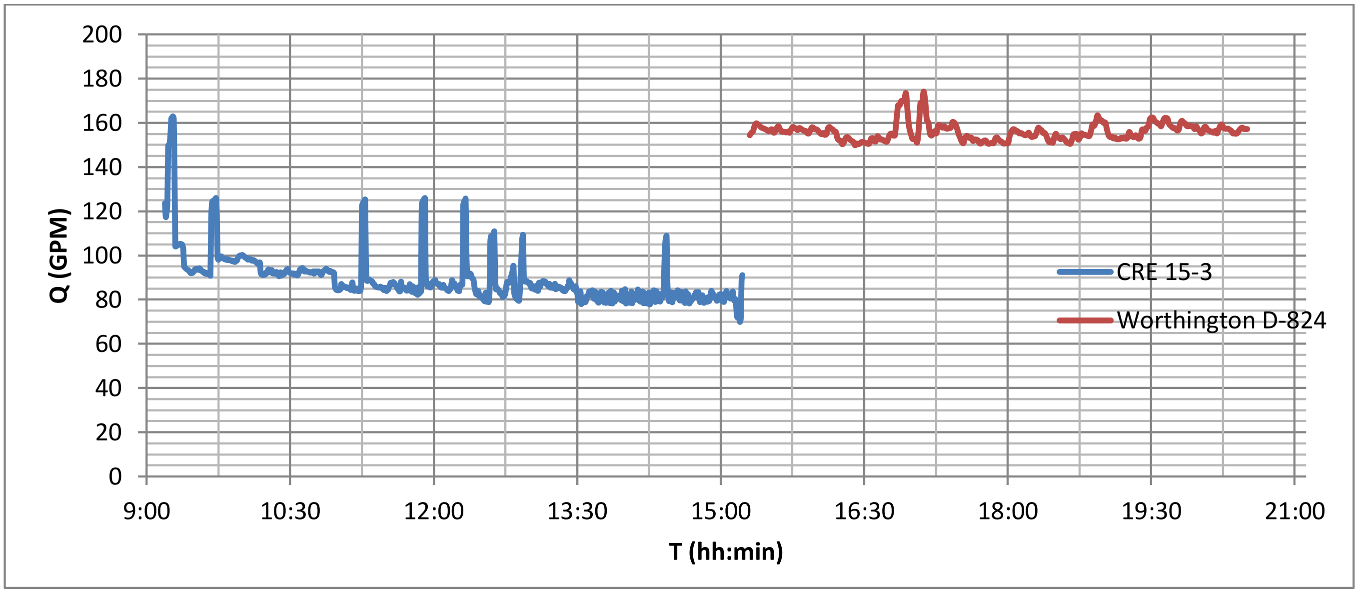


Figure 67: Grundfos CRE 15-3 vs. Worthington D-824 Flow Rate for April 2, 2013.

When plotting the average recorded flow rate and discharge pressure on the Grundfos CRE 15-3 WEBCAPS pump curve, the obtained theoretical power was 1.21 kW (48.9% pump and motor efficiency [41]), just 0.82% lower than the recorded average consumption. With respect to the Worthington D-824 pump, when using the actual average recorded flow rate and discharge pressure on its pump curve, the theoretical average power was 5.22 kW (61% pump efficiency), about 3.87% lower than the average recorded power consumption. The average theoretical power obtained when using the estimated values was 4.18 kW (37% pump efficiency), approximately 2.45% higher than the estimated power consumption if no water was being supplied to the heat exchanger.

Finally, the calculated average hydraulic power found for the Grundfos CRE 15-3 pumps by using Eq. (5) was 1.18 kW (1.59 HP), approximately 3.28% lower than the average recorded power consumption. When using the actual recorded flow rate and discharge pressure, the Worthington D-824 pump's average calculated hydraulic power was 4.73 kW (6.34 HP), approximately 12.9% lower than the average recorded power. By using the estimated values in

Eq. (5), the calculated average hydraulic power was 4.38 kW (5.88 HP), approximately 7.35% higher than the power consumption that was estimated for no water being supplied to the heat exchanger.

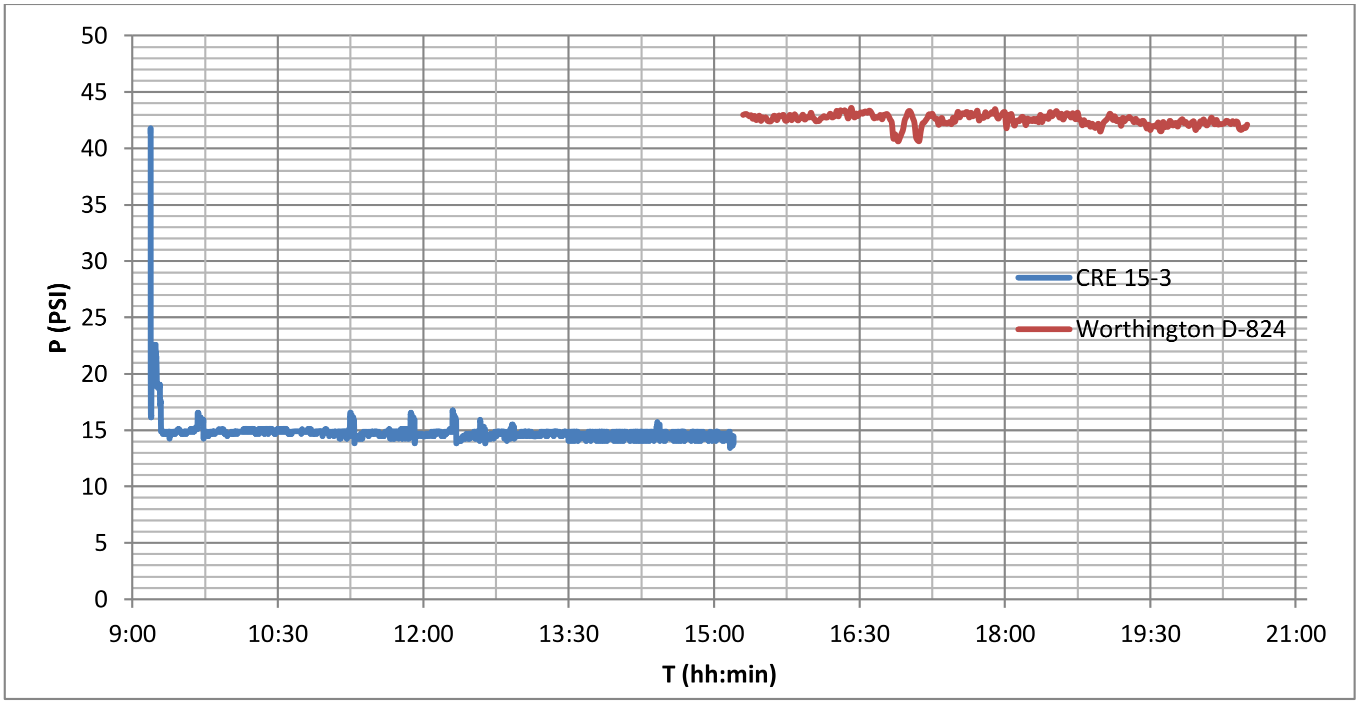


Figure 68: Grundfos CRE 15-3 vs. Worthington D-824 Discharge Pressure for April 2, 2013.

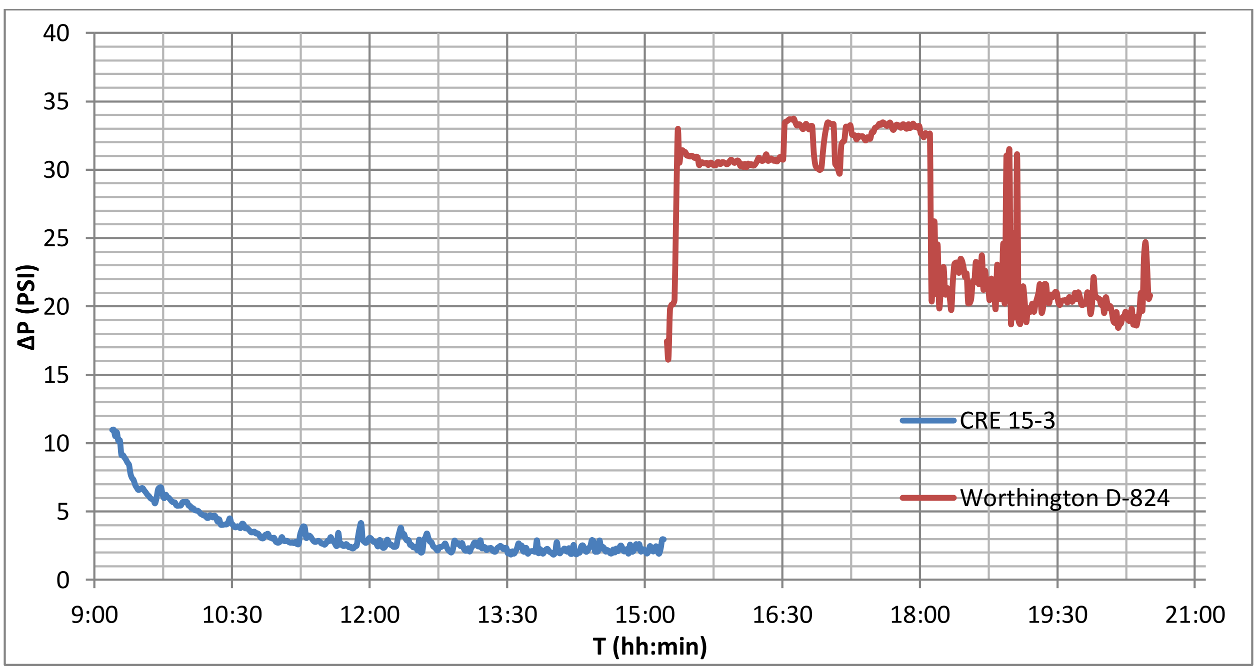


Figure 69: Grundfos CRE 15-3 vs. Worthington D-824 Differential Pressure across Control Valve for April 2, 2013

The average differential pressure across the control valve, shown in Fig. 69, was 3.38 PSI during the time the Grundfos CRE 15-3 pump was in operation. Again, this low differential pressure was due to the fact that the pneumatic system that controls the valve was shut off, causing the valve to remain fully open. In this case, the valve did not control the amount of water being supplied to the deaerator tank, since the CRE 15-3 pumps were doing that by increasing and decreasing the flow of water supplied to the tank based on its water level. When the Worthington D-824 pump was in operation, the average differential pressure across the valve was 26.72 PSI, which is very similar to the values obtained for the previous cases where the heat exchanger valve was open. However, only the Worthington D-824 pump was able to provide water to the heat exchanger in this case, since, when running in level control mode, the discharge pressure of the Grundfos CRE 15-3 pumps was not high enough to be able to provide water for the heat exchanger.

In conclusion, based on the comparisons made in all four cases between the power consumption recorded values and their theoretical calculated values, the data gathered through the sensors and data loggers in this project is reliable enough to be used as the basis for the comparison between energy expenditures in the life cycle cost analysis for the Grundfos CRE 15-3 variable speed pumps and the Worthington D-824 constant speed pump. The rough estimates made in Case 4 make the comparison between the two sets of pumps less trustworthy when compared to the first three cases. Therefore, even though a life cycle cost analysis shall be made for all four cases, one should consider only the first three cases to be more adequate comparisons.

Chapter 4: Life Cycle Cost Analysis

The life cycle cost analysis was performed using the BLCC software provided by the DOE [25], following the procedure shown in Section 2.4 of this document. A total of eight life cycle cost analyses were performed with the BLCC software, i.e., one for Case 1, two for Case 4, and three for Cases 2 and 3. For Case 2, the pumps were used in two different ways: i) pumps supplied water only to the deaerator tank, ii) pumps supplied water to both the deaerator tank and the heat exchanger. The two different analyses for Case 4 include: i) comparing the Worthington D-824 pump supplying water to the deaerator tank and the heat exchanger to the CRE 15-3 pumps just supplying water to the deaerator tank, ii) comparison of both pump systems just supplying water to the deaerator tank based on power consumption estimates made for the Worthington D-824 pump (using data from Case 2). The life cycle cost analyses made for Cases 1 through 3 should be considered more reliable because several more estimates were made in Case 4. These estimates were made in order to try to predict the power consumption of the Worthington D-824 constant speed pump if it only supplied water to the deaerator tank, so that a fair comparison between the power consumption of this pump and that of the Grundfos CRE 15-3 pumps could be made.

As mentioned in Section 2.2 of this document, since the CRE 15-3 pumps' data gathering system did not record the power consumption data in equal intervals like the system used for the Worthington D-824 pump, the average power consumption was used to calculate the energy consumption of both pump systems. Also, the power consumption of the pumps was assumed to be directly related to the steam production of the power plant, i.e., the higher the amount of steam produced by the plant, the higher the power consumed by the pumps, which is due to the amount of water they needed to provide if order for the boilers to meet the steam demands. For this reason, when estimating the average energy consumption for each month in which the power consumption data was gathered, if the average steam production from the days that the data was gathered was close to (within 10%) or higher than the average steam production of that whole month, the average recorded power consumption was then just multiplied by the amount of hours in that month to obtain the average energy consumption (kWh) for the whole month. (Energy consumption values for Cases 1, 2 and 4 were found in this manner.) If the steam produced during the days when power consumption data was recorded was much lower than that month's average steam production (for Case 3), daily average energy consumption values were estimated by multiplying the energy consumption from the day on which data was known, by the ratio of steam production from the desired day to the steam production of the known day. A representation of this estimate can be seen below in equation format (see Appendices G through J for hand calculations and better representations of the estimates made for each Case):

$$Energy\ cons.\ of\ Desired\ Day\ (kWh) =$$

$$energy\ cons.\ known\ day\ (kWh) \times \frac{Desired\ day\ steam\ prod.(lbs)}{Steam\ prod.on\ day\ with\ known\ energy\ cons.(lbs)} \tag{6}$$

To obtain the estimated energy consumption of each pump for the months in which data was not recorded, the energy consumption of the known month (months in which data was gathered) was multiplied by the ratio of steam production from the unknown month to the known month. Once the average energy consumption of every month for a 12 month period was estimated for each Case, these consumption values were added together and input into the BLCC software as being the estimated total annual energy consumption of the pump under consideration. It is important to recall that these calculations are just estimates for the annual energy consumption of each pump system which are used as an input for annual consumption in the BLCC software, so that a life cycle cost analysis could be performed for each case discussed in this document.

With respect to water costs, the BLCC divides the water usage between summer and winter rather than monthly usage. Since the power plant provided information for the amount of water bought from the city for every month, the power plant's water usage from April through September was considered summer and October through March was considered the winter water usage. In all four cases, the same total water usage for their respective 12 month period was applied for both pumps in the life cycle analysis. Also, the seal replacement costs (presented as "Component: Initial Costs" under "Replacement to Capital Components" in Appendices K through P) and labor (presented as "Annually Recurring Costs" under "Operating, Maintenance & Repair Costs" in Appendices K through P) were considered to be the same for both pumps. The costs that were different between the two pumps, besides their energy expenditures and initial purchase costs (presented as "Yearly Cost" under "Initial Capital Costs" in Appendices K through P), were the motor/impeller replacement costs (presented as "Non-Annually Recurring Costs" under "Operating, Maintenance & Repair Costs" in Appendices K through P). It was found that the CRE 15-3 pumps have a higher cost as compared to the Worthington D-824 pump

(US$1,000 for the Worthington D-824 versus US$2,000 for the CRE 15-3) [33]. For this reason, the variables that mainly influenced these pumps' life cycle costs were their initial costs and their energy expenditures and motor/impeller costs. One must recall that all values that the BLCC software provides for energy, water and total life cycle costs are calculated in present value using the equations from Table 1 that are described in Section 2.4 of this document.

4.1 Case 1

In Case 1, both the CRE 15-3 and the Worthington D-824 pumps were running in discharge pressure mode, providing water to both the deaerator tank and the heat exchanger. Since data was gathered starting in February of 2012, in order to have the total energy consumption for 12 months (1 year), calculations were made to obtain energy consumption values from February 2012 through January 2013. The water usage of the plant was also based on the information provided by the power plant staff for these twelve months. See Appendix G for the estimated energy consumption hand calculations made for this case based on the gathered power consumption data. The amount of power consumed by the pumps is directly related to the amount of steam produced by the power plant. Thus, the average power that was necessary to produce steam during the days for which data was gathered could serve as a good estimate of the average power that would be necessary to produce steam during that month. If the average steam production of the day in question was similar (within 10%) to the average daily steam production of the month, the average recorded power consumption could be used to predict the total power consumption in that month. The higher average steam productions were used in these calculations so as not to underestimate the power consumption of the pumps. The average steam generated on the days that data was gathered in February, March and April of 2012 was within 10% of the average of the daily steam production for each of those months. For all Cases, there was no occasion that the average steam production for the days during which data was gathered was higher than 10% as compared to the daily average steam production for the month. However, there were situations wherein the days during which data was gathered had steam production that was more than 10% below the daily average for that month. For these months, the ratios of daily steam production were used to modify the measured energy consumption values (for use in the life cycle cost analysis) so as not to underestimate the cost of the power consumption of the pumps. See tables in Appendix E for the steam production averages.

Based on the gathered data and calculations shown in Appendix G, the Worthington D-824 pump had an estimated energy consumption of 53,394.6 kWh ($4,218.00 average annual cost), while the Grundfos CRE 15-3 pumps' estimated energy consumption was 53,621.5 kWh ($4,236.00 average annual cost). Since this document is taking into consideration a 20 year study period in the life cycle cost analysis of this project, according to the BLLC software calculations, the present value of the total energy cost for the Worthington D-824 pump was $72,599 ($5,109 annual cost), and the present value of the total energy cost for the Grundfos CRE 15-3 pumps was $72,876 ($5,128 annual cost). These values include the annual electricity demand charge of $480.00 that the city of Lawrence charges the power plant every year. This shows that, in a 20 year period, the CRE 15-3 pumps would only consume 226.9 kWh more than the Worthington D-824 pump, which translates into $277 of extra cost. However, taking in consideration the length of the study period, this difference is so minimal that one could consider that both pumps are equivalent in their energy consumption and costs for this case.

With regard to estimated water usage for Case 1 for the 20 year period, i.e., the amount of water that the power plant had to buy from the city, the power plant's water usage was 1,696,280 gallons during the summer periods and 3,659,400 gallons during the winter periods. Even though the water is divided into two different periods, the water cost is still $0.00287 for both winter and summer [31]. The cost in present value of this make-up water according to the BLCC software was $229,021.00 ($16,116.00 annual cost), which was the water usage cost used for both pump system.

Once all replacement costs ($2,000 in seals for both pumps), maintenance (motor/impeller: $2,000 for Worthington D-824 pump and $4,000 for the Grundfos CRE 15-3 pumps), labor ($20,000 for both pumps), energy and water costs were taken in consideration, the total life cycle costs in present value for the Worthington D-824 and Grundfos CRE 15-3 pumps were $332,119.00 ($23,370.00 annual cost) and $342,896.00 ($24,129.00 annual cost), respectively. Therefore, when running in discharge pressure mode, the CRE 15-3 pumps' total life cycle cost was $10,777.00 more than that of the Worthington D-824 pump. As shown on the previous page, this difference is not due to the small difference between the pumps' energy consumption values, but it is due to the differences in the initial capital costs and the motor/impeller replacement costs. Again, for a study period of 20 years, this difference in costs is not very significant when looking at the total amount of money spent on these two pump systems. For this reason, one could say that these pumps have similar life cycle costs when the Grundfos CRE 15-3 pumps are running in discharge pressure control mode, just like the Worthington D-824 pump. See Appendix K for the Detailed LCC Report for Case 1. Table 4 shows a summary of the total life cycle costs for each pump (excluding the water costs since these costs are the same for both pump systems).

Table 4: Case 1 - Total Life Cycle Cost Summary

	Worthington D-824	Grundfos CRE 15-3
Investment Cost	$6,500	$15,000
Energy annual Usage	53,394.6 kWh	53,621.5 kWh
Energy Consumption Costs	$65,181	$65,458
Energy Demand Charges	$7,417	$7,417
Motor/Impeller Costs	$2,000	$4,000
Seals Cost	$2,000	$2,000
Total Life Cycle Cost	$83,098	$93,875

4.2 Case 2

For Case 2, the Grundfos CRE 15-3 pumps ran in discharge pressure mode, just like Case 1, in order to replicate the same work done by the Worthington D-824 constant speed pump. However, this time, two scenarios were produced: i) both pump systems provided water to both the deaerator tank and the heat exchanger, ii) both pump systems provided water only to the deaerator tank by having the heat exchanger access valve closed. Since the data for Case 2 was gathered in April of 2013, the 12 month energy estimates were made from May 2012 through April 2013, based on the energy consumption estimates calculated for April 2013. See Appendix H for the hand calculations for power and energy consumption estimates for Case 2. Again, just as for Case 1, the average steam produced during the days data that was gathered in April (15-18) was higher than (but within 10% of) April's daily average. As discussed in Section 4.1, the average power consumption of the pumps to produce steam during those days served as a good prediction of the average power that would be necessary to produce steam during that month. See the April of 2013 Table in Appendix E for these averages.

4.2.1 Heat Exchanger Access Valve Open

Based on the calculations shown in Appendix H, the estimated annual energy consumption for the Worthington D-824 and the Grundfos CRE 15-3 pumps were 43,620.5 kWh ($3,446.00

annual cost) and 49,410.4 kWh ($3,903.00 annual cost), respectively. For the 20 year life cycle cost period, the present value of the total energy consumption cost for the Worthington D-824 pump was $60,667.00 ($4,269.00 annual cost including the $480.00 electricity demand charges), and for the CRE 15-3 pumps, it was $67,735.00 ($4,766.00 annual cost including the $480.00 electricity demand charges). The CRE 15-3 pumps had $7068.00 more in electricity costs in the 20 year study period than the Worthington D-824 pump. This difference is higher than that found in Case 1, which could be due to the different month in which the data was gathered for the pumps. However, the difference is still minimal based on the length of the study period, showing that the pumps still have similar energy consumption values when the Grundfos CRE 15-3 pumps are running in discharge pressure mode. Also, this calculation does not account for differences between the pump flow rates versus power over their operational time periods (see Figs. 38-49).

Based on the amount of make-up water shown in the tables in Appendix E, for Case 2, the power plant's water usage was 2,055,900 gallons during the summer and 4,391,860 gallons during the winter. For a total of 20 years, the present value [calculated by the BLCC software] of money spent on water based on these quantities was $275,720.00 ($19,402.00 annually), which was used in the life cycle cost analysis for both pump systems.

The total life cycle cost in present value for the Worthington D-824 pump was $366,887.00 ($25,817 annual value), and $384,455.00 ($27,053.00 annual value) for the Grundfos CRE 15-3 pumps. Therefore, in a 20 year study period, to run and maintain the Grundfos CRE 15-3 pumps, it would cost $17,568.00 more than when using the Worthington D-824 pump (about $1236.00 difference per year). This shows that, for pump operation in discharge pressure mode as in this part of Case 2, it would not be advantageous to have a variable speed pump in this application due to its initial cost and the relatively similar energy consumption as compared to the Worthington D-824 pump. See Appendix L for the Detailed LCC report for this part of Case 2. Table 5 shows a summary of the total life cycle costs for each pump (excluding the water costs).

Table 5: Case 2 Heat Exchanger Valve Open - Total Life Cycle Cost Summary

	Worthington D-824	Grundfos CRE 15-3
Investment Cost	$6,500	$15,000
Energy annual Usage	43,620.5 kWh	49,410.4 kWh
Energy Consumption Costs	$53,250	$60,318
Energy Demand Charges	$7,417	$7,417
Motor/Impeller Costs	$2,000	$4,000
Seals Cost	$2,000	$2,000
Total Life Cycle Cost	$71,167	$88,735

4.2.2 Heat Exchanger Access Valve Closed - Method A

The 12 month period in which the energy consumption data was estimated for this section is the same as in Section 4.2.1, i.e., May of 2012 through April of 2013. Since the period is the same, the make-up water amount and cost is also the same for both pump systems. The only difference is that their total energy consumption now consists of the energy needed to only supply water to the deaerator tank. See Appendix H for energy consumption hand calculations for Case 2 when heat exchanger value was closed.

With the heat exchanger access valve closed, the Worthington D-824 pump had an estimated annual energy usage of 32,879 kWh ($2,597.00 average annual cost), while for the Grundfos CRE 15-3 pumps, their annual energy usage was estimated to be 24,037.1 kWh ($1,899.00 average annual cost). In present value, for the 20 year study period, the total energy cost to run the Worthington D-824 pump was $47,557.00 ($3,346.00 annual value), and $36,760.00 ($2,587.00 annual value) for the Grundfos CRE 15-3 pumps. This shows that, if the power plant did not have to supply water for the heat exchanger, when running in discharge pressure mode, the CRE 15-3 pumps would save $10,797.00 in energy costs as compared to the Worthington D-824 pump. This projection is not taking into account how much steam would be lost into the atmosphere and how much extra water would have to be bought from the city if all of this steam is lost, which would increase the water expenses that the power plant has; not to mention that the heat exchanger would not be helping maintain the temperature of the water that the system needs in order to keep the plant's efficiency high as discussed in Section 1.4 of this document. Also, from a financial perspective, based on the size of the operations that the power plant has, a $688 annual value difference could be not considered that significant when compared to the difference in the initial capital cost of these two pump systems.

The total life cycle cost for running the Worthington D-824 pump based on present value was $353,775.00 ($24,894.00 annual value), while for the Grundfos CRE 15-3 pumps, it was $353,481.00 ($24,874.00 annual value). In a 20 year period, the CRE 15-3 pumps would only be saving the power plant $294.00, which again shows how these pumps are fairly equivalent in expenses in a 20 year study period. Hence, even though the CRE 15-3 pumps save some money in energy costs, they do not justify the initial investment costs. See Appendix M for the detailed LCC report for this case. Table 6 shows a summary of the total life cycle costs for each pump (excluding the water costs).

Table 6: Case 2 - Heat Exchanger Valve Closed - Method A - Total Life Cycle Cost Summary

	Worthington D-824	Grundfos CRE 15-3
Investment Cost	$6,500	$15,000
Energy annual Usage	32,879.0 kWh	24,037.1 kWh
Energy Consumption Costs	$40,137	$29,343
Energy Demand Charges	$7,417	$7,417
Motor/Impeller Costs	$2,000	$4,000
Seals Cost	$2,000	$2,000
Total Life Cycle Cost	$58,054	$57,760

4.2.3 Heat Exchanger Access Valve Closed - Method B

Whenever the heat exchanger valve is closed, it is assumed that all the water that is supplied by the CRE 15-3 pumps or the Worthington D-824 pump flows into the deaerator tank, and is all turned into steam given there is no recirculation of water back to the condensate storage tanks. For this reason, another method that can be used to find each pump's energy consumption in this situation is to divide the average power consumption of each pump by their respective average flow rate (kW/GPM). Once this is found, these units can be converted to (kJ/lb (mass)) in order to find approximately how much energy each pump consumes to essentially produce a pound of steam. (See Appendix H.1 for hand calculations.) Since the power plant staff provided the information of the total pounds of steam produced for a 12 month period, one is able to calculate the estimated annual energy consumption of each pump. Again, this only works in situations when one knows the exact flow rate that is only being provided to the deaerator tank, since the assumption that all that water is tuned into steam is then valid.

While the heat exchanger valve was closed, the CRE 15-3 pumps estimated energy consumption was 0.2571 kJ for every pound of steam produced. This means that, for the total amount of steam produced from May 2012 through April 2013 (285,974,601 lbs) the CRE 15-3 energy consumption was 20,423.5 kWh. This energy consumption is 15% lower than the value obtained from the calculations used in “Method A” (24,037.1 kWh). With respect to the Worthington D-824 pump, its estimated energy consumption was 0.3897 kJ for every pound of steam produced; translating to an estimated annual energy consumption of 30,957 kWh. This energy consumption is 5.85% lower than the value obtained from the calculations in “Method A”. Since these are estimates for a long 20 years study period, the differences between these two methods are reasonable, given the two different approaches used to calculate them. Also, since the results obtained are fairly close, this shows that “Method A”, for this situation in particular, is a reasonable approach to estimating the energy consumption of both pump systems in the cases for which “Method B” cannot be used, i.e., Case 1, Case 2 (when the heat exchanger valve is open), and Case 4.

Based on the estimated annual energy consumptions discussed previously, the Worthington D-824 pump would have an average annual energy cost of $2,446. For the 20 year study period, in present value, the Worthington D-824 pump total energy cost would be $45,208 (annual value of $3,181). With respect to the CRE 15-3 pumps, the average annual energy cost would be $1,613. For the 20 year study period, the present value of their total energy costs would be $32,349 ($2,276). Therefore, in this study period, the CRE 15-3 pumps would save the power plant $12,859 in energy costs (about $2000 more than what was found in Method A). Taking into consideration all of the other costs, the total life cycle costs for the Worthington D-824 pump and the CRE 15-3 pumps are $351,428 ($24,729 annual value) and $349,070 ($24,563 annual value), respectively. Even though the CRE 15-3 pumps could save the plant $12,859 in energy costs, which for a 20 year study period is not a substantial amount since this amount would not cover the pumps’ initial cost, the present value of the total life cycle cost only shows a $2,358 total savings. (See Appendix M.1 for the detailed LCC for this case.) Table 6 shows a summary of the total life cycle costs for each pump (excluding the water costs).

Table 7: Case 2 - Heat Exchanger Valve Closed - Method B - Total Life Cycle Cost Summary

	Worthington D-824	Grundfos CRE 15-3
Investment Cost	$6,500	$15,000
Energy annual Usage	30,957.0 kWh	20,423.5 kWh
Energy Consumption Costs	$37,791	$24,932
Energy Demand Charges	$7,417	$7,417
Motor/Impeller Costs	$2,000	$4,000
Seals Cost	$2,000	$2,000
Total Life Cycle Cost	$55,708	$53,349

4.3 Case 3

In Case 3, both the Worthington D-824 and the CRE 15-3 pumps were just supplying water to the deaerator tank. However, this time the CRE 15-3 pumps were running in level control mode, where the pumps would increase and decrease water flow to maintain a constant level of water in the deaerator tank. The 12 month period used to obtain the annual energy consumption values for Case 3 was just like the one for Case 2, i.e., May of 2012 through April of 2013. Since the data for this case was just obtained on April 30th, 2013, and due to the fact that the steam produced that day was much lower than the monthly's average (621,600 lbs versus 859,550 lbs), calculations had to be made to estimate the energy consumption of every unknown day of April, before monthly estimates could be made for the remaining months in order to get a better estimate. See Appendix I for the hand calculations made to obtain the energy consumption estimates for this case.

4.3.1 Method A

Based on the calculations shown in Appendix I, the average annual energy consumption was 42,426.8 kWh ($3,352.00 average annual cost) for the Worthington D-824 pump, and 8,827.5 kWh ($697.00 average annual cost) for the Grundfos CRE 15-3 pumps. Based on these estimated annual energy consumption values, in the 20 year study period for this life cycle cost analysis, the present value of total energy costs was $59,210.00 ($4,166.00 annual value) for the Worthington D-824 pump, and $18,193.00 ($1,280.00 annual value) for the Grundfos CRE 15-3 pumps. Hence, if the CRE 15-3 pumps were operated in level control mode, based in this case, the power plant could save $41,017.00 in energy costs in a period of 20 years based on present values. Again, this is not taking into consideration how much extra money the plant would have to spend to purchase extra water from the city due to the steam that is not recycled by the heat exchanger as well as the decrease in the plant's efficiency for not using the heat exchanger as discussed in Section 1.4. Also, not being taken into account is the potential use of a different set of variable speed pumps which could be able to provide a water supply to the heat exchanger.

Since the 12 month period used in this case is the same as Case 2, the summer and winter water usages are also the same, 2,055,900 gallons and 4,391,860 gallons, respectively. Therefore, for the 20 years being analyzed in this life cycle cost analysis, based on present value, the power plant would have $275,720.00 ($19,402.00 annual value) in water usage costs.

The total life cycle cost for 20 years based on present value was $365,430.00 ($25,714.00 annual value) for the Worthington D-824 pump, and $334,914.00 ($23,567.00 annual value) for the Grundfos CRE 15-3 pumps. Hence, taking into account all the costs the power plant would have to run these two pump systems, in 20 years, the CRE 15-3 pumps would save the plant $30,516.00. Based on the three cases presented in this document so far, this is the biggest savings the CRE 15-3 pumps would be able to provide the power plant when compared to the Worthington D-824 constant speed pump. Case 3 does not consider that the pumps provide water to the heat exchanger, leaving out the extra make-up water expenses necessary to compensate for the steam lost; nor does it consider employing a different set of variable speed pumps which could be designed to allow water flow to reach the heat exchanger, or moving the heat exchanger to a lower location in the plant. However, if this issue is neglected, one could say that this case shows how the CRE 15-3 pumps could save major energy expenses for the power plant when running in level control mode. See Appendix N for a detailed LCC report. Table 8 shows a summary of the total life cycle costs for each pump (excluding the water costs).

Table 8: Case 3 - Method A - Total Life Cycle Cost Summary

	Worthington D-824	Grundfos CRE 15-3
Investment Cost	$6,500	$15,000
Energy annual Usage	42,426.8 kWh	8,827.5 kWh
Energy Consumption Costs	$51,792	$10,776
Energy Demand Charges	$7,417	$7,417
Motor/Impeller Costs	$2,000	$4,000
Seals Cost	$2,000	$2,000
Total Life Cycle Cost	$69,709	$39,193

4.3.2 Method B

This method follows the same calculations procedures as explained in Section 4.2.3 of this document. This method could be used in this case, since both pump systems were again only supplying water to the deaerator tank. Based on the calculations shown in Appendix I.1, the estimated average annual energy consumption was 38,699.8 kWh ($3,057 average annual cost) for the Worthington D-824 pump and $8,151.7 kWh ($644 average annual cost) for the CRE 15-3 pumps. The Worthington D-824 estimated annual energy consumption found with Method B is 8.78% lower than the value obtained using Method A. On the other hand, the CRE 15-3 pumps' estimated annual energy consumption from Method B was 7.66% lower as compared to the one found using Method A. Again, these differences show that, for this situation, both methods are reasonable approaches to calculating the energy consumption of the pump systems being discussed.

For the 20 year study period, the total energy costs in present value were $54,660 ($3,846 annual value) for the Worthington D-824 pump and $17,368 ($1,222 annual value) for the CRE 15-3 pumps. The CRE 15-3 pumps would save the power plant $37,292 in energy costs when running in level control mode while supplying water only to the deaerator tank. These savings surpass the investment costs of the pumps and could justify using the CRE 15-3 pumps; however, just as in Section 4.3.1, the extra water costs and lower boiler efficiency for not using the heat exchanger are not taken into account in this calculation. The total life cycle costs (in present value) for the Worthington D-824 pump and the CRE 15-3 pumps would be $360,880 ($25,394 annual value) and $334,089 ($23,509 annual value), respectively. Therefore, excluding the possible extra water costs, the CRE 15-3 pumps could potentially save the power plant $26,791 when running in level control mode and providing water just to the deaerator tank. See Appendix N.1 for the detailed LCC report. Table 9 shows a summary of the total life cycle costs for each pump (excluding the water costs).

Table 9: Case 3 - Method B - Total Life Cycle Cost Summary

	Worthington D-824	Grundfos CRE 15-3
Investment Cost	$6,500	$15,000
Energy annual Usage	38,699.8 kWh	8,151.7 kWh
Energy Consumption Costs	$47,243	$9,951
Energy Demand Charges	$7,417	$7,417
Motor/Impeller Costs	$2,000	$4,000
Seals Cost	$2,000	$2,000
Total Life Cycle Cost	$65,160	$38,368

4.4 Case 4

In Case 4, the Worthington D-824 and the Grundfos CRE 15-3 pumps were supposed to supply water to both the deaerator tank and the heat exchanger while CRE 15-3 pumps ran in level control mode. However, due to the low discharge pressure of the CRE 15-3 pumps when running in level control mode, they were able to provide water only to the deaerator tank, while the Worthington D-824 pump did supply water to both the deaerator tank and the heat exchanger. For this reason, the two pumps could not be fairly compared when using the gathered data, since the Worthington D-824 constant speed pump was doing more work than the CRE 15-3 pumps by supplying water to areas that the variable speed pumps could not. The life cycle cost analysis for this comparison will be shown in Section 4.4.1, and Section 4.4.2 will show an estimated life cycle cost analysis which attempts to account for the extra power consumption that the Worthington D-824 pump was required to use in order to supply water to the heat exchanger. The estimates accounting for extra power consumption were based on the data gathered for Case 2. For Case 2, when the heat exchanger access valve was closed with the Worthington D-824 pump in operation, its power consumption had an average drop of approximately 1.345kW as compared to the power consumption measured when the heat exchanger valve was open. Therefore, by subtracting this average power consumption drop from the actual power consumption of the Worthington D-824 pump for this case, it is assumed that this value would represent the power necessary to provide water only to the deaerator tank (just like the job that the Grundfos CRE 15-3 pumps were doing). Again, these are rough estimates which attempted to take into consideration the data gathered for Case 4. See Appendix J for the hand calculations made to obtain the energy consumption values used in Sections 4.4.1 and 4.4.2.

4.4.1 Considering Heat Exchanger for Worthington D-824

The 12 month period used to obtain estimated energy consumption values for Case 4 was April of 2012 through March of 2013. These consumption values were based on known recorded data from March of 2013. Just like Cases 1 and 2, since the average steam produced during the days (March 11, 12, 14, 18, 19, 20, 21 and 26) that data was gathered for this case was slightly higher than the average daily steam production in the month of March (1,200,600 lbs versus 1,112,955 lbs for the monthly average), it was not necessary to estimate daily energy consumption for this case. The average power consumption for those days would be similar to the power consumption necessary to produce the month's average steam production. Again that is because the average power consumptions for the days during which data was gathered are a good representation for the power that was necessary to produce the average amount of steam that month.

Based on the hand calculations shown in Appendix J, the estimated average annual energy consumption for the Worthington D-824 pump when supplying water to the deaerator tank and the heat exchanger was 33,001.5 kWh ($2,607.00 average annual cost), while the estimated average annual consumption for the Grundfos CRE 15-3 pumps when supplying water just to the deaerator tank was 10,227.4 kWh ($808.00 average annual cost). Considering the life cycle cost 20 year study period, the total present value of the energy cost was $47,704.00 ($3,357.00 annual value, including the $480.00 energy demand charge cost) for the Worthington D-824 pump, and $19,902.00 ($1,400.00 annual value including the $480.00 energy demand cost) for the Grundfos CRE 15-3 pumps. Based on these present value costs, the CRE 15-3 pumps, when running in level control mode, could save about $27,802.00 in energy costs for the power plant. However, this is not a fair comparison in costs, since, in this scenario, the Worthington D-824 pump is supplying water to the heat exchanger and the deaerator tank, while the CRE 15-3 pumps are only supplying water to the deaerator tank.

For the 12 month period being discussed in Case 4, the average water usage during the summer months for the power plant was 1,696,280 gallons ($4,868.00 average annual cost), and 4,391,860 gallons (12,605.00 average annual cost) for the winter months. These were the quantities input into the BLCC software for both pump systems in order for it to calculate the present value expenses that the power plant would have when buying water from the city of Lawrence in the 20 year study period. In present value, based on the annual water consumption displayed above, the total water usage costs for a 20 year study period that the power plant would have was $260,342.00 ($18,320.00 annual value).

When taking in consideration the costs mentioned above together with the initial capital costs, labor, maintenance and replacement costs for each respective pump system (refer to Section 2.4 for the exact value of these costs), the total life cycle cost in present value was $338,546.00 ($23,823.00 annual value) for the Worthington D-824 pump, and $321,245.00 ($22,605.00 annual value) for the Grundfos CRE 15-3 pumps. Based on these present value costs from the BLCC software, in 20 years, the power plant would have $17,301.00 in savings by running the CRE 15-3 pumps in level control mode when compared to the Worthington D-824 constant speed pump. In this case, the pumps were doing two different levels of work. Therefore, Section 4.4.2 will provide different life cycle costs by estimating the power consumption of the Worthington D-824 pump if it only supplied water to the deaerator tank. See Appendix O for the detailed LLC report for this part of Case 4. Table 10 shows a summary of the total life cycle costs for each pump (excluding the water costs).

Table 10: Case 4 - Considering Heat Exchanger - Total Life Cycle Cost

	Worthington D-824	Grundfos CRE 15-3
Investment Cost	$6,500	$15,000
Energy annual Usage	33,001.5 kWh	10,227.4 kWh
Energy Consumption Costs	$40,286	$12,485
Energy Demand Charges	$7,417	$7,417
Motor/Impeller Costs	$2,000	$4,000
Seals Cost	$2,000	$2,000
Total Life Cycle Cost	$58,203	$40,902

4.4.2 NOT Considering Heat Exchanger for Worthington D-824

As mentioned in Section 4.4, based on the data gathered for Case 2, whenever the Worthington D-824 pump was in operation and the heat exchanger access valve was closed, its power consumption would drop an average of 1.345 kW (based on the 4 days of data gathering for Case 2). Assuming that this was the extra amount of power required by the Worthington D-824 pump to supply water to the heat exchanger, this value was subtracted from the average power consumption calculated in Case 4, in order to estimate the energy consumption for the Worthington D-824 pump when just supplying water to the deaerator tank. By using these estimated values, the goal was to provide a more representative comparison of the energy costs in the life cycle cost analysis of the two pump systems being studied. Again, these are rough estimates, and one should consider the analyses performed for Cases 1 through 3 to be more reliable than this Case. See Appendix J for the hand calculations made to estimate the annual energy consumptions used in Case 4.

Once the estimated energy usage for the Worthington D-824 pump was made, disregarding the power necessary to supply water to the heat exchanger, the estimated average annual energy usage for the Worthington D-824 pump was 24,912.9 kWh ($1,968.00 average annual cost). Since no new calculations were required for the Grundfos CRE 15-3 pumps, their estimated annual energy usage remained at 10,227.4 kWh ($808.00 average annual cost). With this new consumption, based on present value, for a 20 year study period, the energy costs for the Worthington D-824 pump became $37,830.00 ($2,662 annual value), while the energy costs for the Grundfos CRE 15-3 pumps continued to be $19,902.00 ($1,400.00 annual value). Therefore, even when estimating the energy consumption required for the Worthington D-824 pump to supply water only to the deaerator tank, based solely on energy costs, in 20 years the power plant would have a savings of $17,928.00 when using the Grundfos CRE 15-3 pumps in level control mode. However, one must recall, that not considered is the probable extra water costs that the power plant would have for not reusing the steam that is being lost into the atmosphere when not using the heat exchanger and not redesigning with different variable speed pumps.

The water usage and its costs for this section are the same as the values presented in Section 4.4.1 since this section is dealing with the same 12 month period and water usage information. This means that for a 20 year period, the present value of the water cost being used in the life cycle analysis of both pump system still would be $260,342.00 ($18,320 annual value). See Appendix E for the monthly make up water and steam production tables.

The total life cycle cost (for a 20 year life period) based on present value would then be $328,672.00 ($23,128.00 annual value) for the Worthington D-824 pump, and $321,245.00 ($22,605.00) for the Grundfos CRE 15-3 pumps, when considering all of the initial capital, labor, energy, water, and maintenance costs. Even though the CRE 15-3 pumps showed very substantial savings in energy costs as compared to the Worthington D-824 pump ($17,928.00), the total life cycle cost only shows $7,427.00 in saving in 20 years. This is because of the CRE 15-3 pumps' higher initial capital cost as well as the higher costs when replacing motor/impellers. However, based exclusively on energy costs, the CRE 15-3 pumps are bound to provide quite substantial savings when compared to the Worthington D-824 pump. See Appendix P for the detailed LCC report for this part of Case 4. Table 10 shows a summary of the total life cycle costs for each pump (excluding the water costs).

Table 11: Case 4 - NOT Considering Heat Exchanger - Total Life Cycle Cost

	Worthington D-824	Grundfos CRE 15-3
Investment Cost	$6,500	$15,000
Energy annual Usage	24,912.9 kWh	10,227.4 kWh
Energy Consumption Costs	$30,412	$12,485
Energy Demand Charges	$7,417	$7,417
Motor/Impeller Costs	$2,000	$4,000
Seals Cost	$2,000	$2,000
Total Life Cycle Cost	$48,329	$40,902

Chapter 5: Summary and Conclusions

In this chapter a summary of the work is presented in this document and conclusions are drawn.

Summary

(1) The data presented in Chapter 3 for Case 1 showed how the Grundfos variable speed pumps had an equivalent performance to the Worthington D-824 constant speed pump with regard to flow rates, discharge pressure, differential pressure across the control valve. Even, though at times the Grundfos CRE 15-3 pumps required more power to run, for the most part, the power consumption of both pump systems were within 7.5% of each other when running in discharge pressure mode.

(2) With regard to the data gathered for Case 2 while having the heat exchanger access valve closed, the only similarity both pump systems had was the flow rate of water that they supplied to the deaerator tank. The discharge pressure of the Worthington D-824 pump was about 5 PSI higher than the discharge pressure of the Grundfos CRE 15-3 pumps, consequently making the differential pressure across the control valve also higher as compared to the times the Grundfos variable speed pumps were running. Also, for this set of data, the Grundfos pump power consumption was approximately 27% lower than the Worthington D-824 constant speed pump. On the other hand, when these pump systems ran while the heat exchanger access valve was open, they both had comparable values for their discharge pressure, flow rates and differential pressure across the control valve. However, for this case, the Grundfos CRE 15-3 pumps did have power consumption about 11.7% higher than that of the Worthington D-824 pump.

(3) Based on the data gathered for Case 3, the only similarity the Grundfos CRE 15-3 pumps and the Worthington D-824 pump had was the flow rate of water that they provided to the system. Since in this case both pump systems were just supplying water to the deaerator tank, and the Grundfos CRE 15-3 pumps were running in level control mode, their discharge pressure was much lower by having the control valve fully open during its operation. The Grundfos CRE 15-3 pumps' power consumption was about 79% lower than that of the Worthington D-824 pump in this scenario.

(4) In Case 4, the Worthington D-824 constant speed pump was supplying water to both the deaerator tank and the heat exchanger, while the Grundfos variable speed pumps were only supplying water to the deaerator tank due to the low discharge pressure when running in level control mode. For this reason, the results presented for this case show higher values for discharge pressure, flow rate, differential pressure across the control valve, and power consumption. (For the times in which the Worthington D-824 was in operation, its power consumption was 63% higher than the Grundfos CRE 15-3 pumps power consumption.) However, even after estimates were made in attempt to account for the extra power needed by the Worthington D-824 pump to supply water to the heat exchanger, the calculations still showed that the Worthington D-824 pump power consumption was 52% higher as compared to the Grundfos CRE 15-3 pumps' power consumption.

(5) All of the power consumption gathered data for all cases discussed above were compared to theoretical data from the pump curves of each respective pump as well as to hydraulic pump power calculations. All theoretical values were similar to the theoretical data (within 10% to 15%), which confirmed that the data gathered could be used to perform a life cycle analysis in order to compare the costs of the Grundfos CRE 15-3 pumps to the costs of the Worthington D-824 pump in a 20 years study period.

Conclusions

(1) The life cycle cost analysis performed for Case 1 showed that, when running the Grundfos CRE 15-3 pumps in discharge pressure mode, they would have fairly equivalent energy expenses as compared to the Worthington D-824 pump ($72,876.00 vs. $72,599.00). The Grundfos CRE 15-3 pumps had a higher total life cycle cost, due to their initial capital cost ($342,896.00 vs. 332,119.00), showing that for this application, it would not be advantageous to use a variable speed pump as compared to the Worthington D-824 pump.

(2) When supplying water just to the deaerator tank in Case 2 using "Method A", The Grundfos CRE 15-3 pumps had lower energy expenditures as compared to the Worthington D-824 pump's energy costs ($36,760.00 vs. $47,554.00). However, due to

the variable speed pumps' higher initial capital costs, the total life cycle costs for both pump systems were fairly similar, $353,775.00 for the Worthington D-824 pump and $353,481.00 for the Grundfos CRE 15-3 pumps. Therefore, even though there was energy savings while using the variable speed pumps, such savings did not help lower the total life cycle cost as compared to the costs needed to operate the constant speed pump. "Method B" showed lower energy expenditures for both pump systems ($32,349 for the CRE 15-3 pumps vs. $45,208 for the Worthington D-824 pump), which are still fairly comparable to the results obtained using "Method A", where "Method B" is the best method analytically. Due to the CRE 15-3 pumps higher investment costs, Method B also showed very similar total life cycle costs for both pump systems: $351,428 for the Worthington D-824 pump and $349,070 for the CRE 15-3 pumps,

(3) For the scenario in Case 2 for which both pump systems provided water to both the deaerator tank and the heat exchanger, the Grundfos CRE 15-3 pumps had higher energy costs as compared to the Worthington D-824 pump ($67,735.00 vs. $60,667.00). The total life cycle cost for the Grundfos CRE 15-3 pumps was $384,455.00, while the total life cycle cost for the Worthington D-824 pump was $366,887.00. This shows that, in this scenario, from an economics perspective, it would be advantageous to use the Worthington D-824 pump to supply water to the system due to its lower initial capital costs and energy costs.

(4) Case 3 is the scenario that showed the Grundfos CRE 15-3 pumps would be more advantageous to supply water to the system, when only supplying water to the deaerator tank in the power plant. For the 20 years study period, the total energy costs when using the Grundfos CRE 15-3 pumps was $18,193.00, while the total energy costs to run the Worthington D-824 pumps was $59,210.00. The total life cycle costs for the Grundfos CRE 15-3 pumps and the Worthington D-824 pump were $334,914.00 and $365,430.00, respectively. Since in 20 years the Grundfos CRE 15-3 pumps could potentially save the plant approximately $30,516.00, one could say that it would be advantageous to equip the power plant with this type of pump. However, this is not considering the amount of steam that is being lost when not supplying water to the heat exchanger, nor does it consider the possibility of redesigning for different variable speed pumps or moving the heat

exchanger to a lower location. Therefore, when simply considering energy costs, the Grundfos CRE 15-3 pumps would be the best option when supplying water just to the deaerator tank. “Method B” in Case 3, confirmed that this mode of operation would justify the use of the CRE 15-3 pumps in this application instead of the Worthington D-824 pump. The total energy costs when using the Grundfos CRE 15-3 pumps was $17,368 and $54,660 when using the Worthington D-824 pumps ($37,292 in savings when using the CRE 15-3 pumps). The total life cycle costs for the CRE 15-3 pumps and the Worthington D-824 pump were $334,089 and $360,880, respectively. These total life cycle costs translate to $26,791 in total savings when using the CRE 15-3 pumps to supply water only to the deaerator tank.

(5) In Case 4, even after performing the calculations to account for the extra power that the Worthington D-824 pump required to provide water to the heat exchanger in order to obtain its energy consumption, the Grundfos CRE 15-3 pumps still had lower energy consumption costs ($19,902.00 vs. $37,830.00). The total life cycle cost for the Worthington D-824 pump and the Grundfos CRE 15-3 pumps for the 20 years study period were $328,672.00 and $321,245.00, respectively. Again, just as in Case 3, the amount of steam being lost by not using the heat exchanger, possibly making the power plant have extra water costs, was not accounted for in this application. Therefore, even though the Grundfos CRE 15-3 pumps had smaller energy consumption costs, the total life cycle costs of both pump systems were still fairly similar, due to the higher initial capital costs required to purchase the variable speed pumps.

In conclusion, all cases presented in this document, with the exception of Case 3, show that the Grundfos CRE 15-3 variable speed centrifugal pumps and the Worthington D-824 constant speed centrifugal pump have very similar total life cycle costs, even though the Grundfos pumps had lower energy costs when running in level control mode in Case 4. However, in all cases in which the Grundfos CRE 15-3 pumps ran using level control mode, significant energy savings were obtained as compared to the energy consumption of the Worthington D-824 pump. This shows, for the most part, that the higher initial investment cost to obtain this particular design of variable speed pumps would not be advantageous for this specific application. The Grundfos CRE 15-3 pumps could be much more advantageous and cost effective in applications in which a constant supply of liquid was not necessary, since then these pumps would only run when the supply of liquid was necessary and be on standby when the demand was met. In this steam power plant application, such pumps are required to be constantly running in order to provide water to the deaerator tank and heat exchanger. Case 3 showed the greatest savings when running the Grundfos CRE 15-3 pumps in level control mode. For this reason, future studies should be performed in order to assess the extra costs that the power plant would have from the steam lost when not using the heat exchanger. In case the extra costs incurred by the steam being lost when not using the heat exchanger are minimal, it could still be justifiable to use the Grundfos CRE 15-3 pumps in level control mode to just supply water to the deaerator tank.

Recommendations

When running the Grundfos CRE 15-3 pumps in level control mode, the minimum and maximum speeds of the pumps had to be manually altered until optimal minimum and maximum speeds were obtained based on the amount of water needed by the system. Research on an algorithm for the pumps' controller is encouraged so that these optimal speeds are automatically established by the pumps' controller. If not, in order to run these pumps in an application such as the one discussed in this document, a person would have to be put in charge of making sure the pumps' minimum and maximum speeds satisfied the systems' water demand every time the CRE 15-3 pumps were in operation.

It is also recommended to measure the flow of water being provided by the pumps to the heat exchanger, since this was a piece of information that was estimated in this project. Also, a new variable speed pump with different characteristics could be tested in this application in order to find out if it would be able to provide water to both the deaerator tank and the heat exchanger in level control mode. The relocation of the heat exchanger to a lower area in the power plant should be looked into, since that would allow it to be used even when a pump's discharge pressure is low. Finally the installation of a variable speed pump that would be dedicated to supply water only to the heat exchanger should be investigated.

Appendix A: Affinity Laws [43]

The Affinity Laws state that:

(1) Flow (GPM) will change directly when there is a change in speed (RPM) or diameter (inches).

(2) Heads (feet) will change as the square of a change in speed (RPM) or diameter (inches).

(3) BHP (HP) will change as the cube of a change in speed (RPM) or diameter (inches). The Brake Horsepower is the amount of real horsepower going to the pump, and not the horsepower used by the motor.

The formulas for the Affinity Laws are expressed below.

$$\frac{Q_1}{Q_2} = \frac{D_1}{D_2} \quad \text{OR} \quad \frac{Q_1}{Q_2} = \frac{N_1}{N_2}$$

$$\frac{H_1}{H_2} = \left(\frac{D_1}{D_2}\right)^2 \quad \text{OR} \quad \frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2$$

$$\frac{BHP_1}{BHP_2} = \left(\frac{D_1}{D_2}\right)^3 \quad \text{OR} \quad \frac{BHP_1}{BHP_2} = \left(\frac{N_1}{N_2}\right)^3$$

Where:

Q = Flow
D = Impeller Diameter
N = Speed
H = Head (TDH)
BHP = Brake Horsepower

The subscript 1 indicates "existing conditions"; the subscript 2 indicates "new" conditions.

This Table was reproduced directly from Reference 43

Appendix B: Pump Curves and Specifications

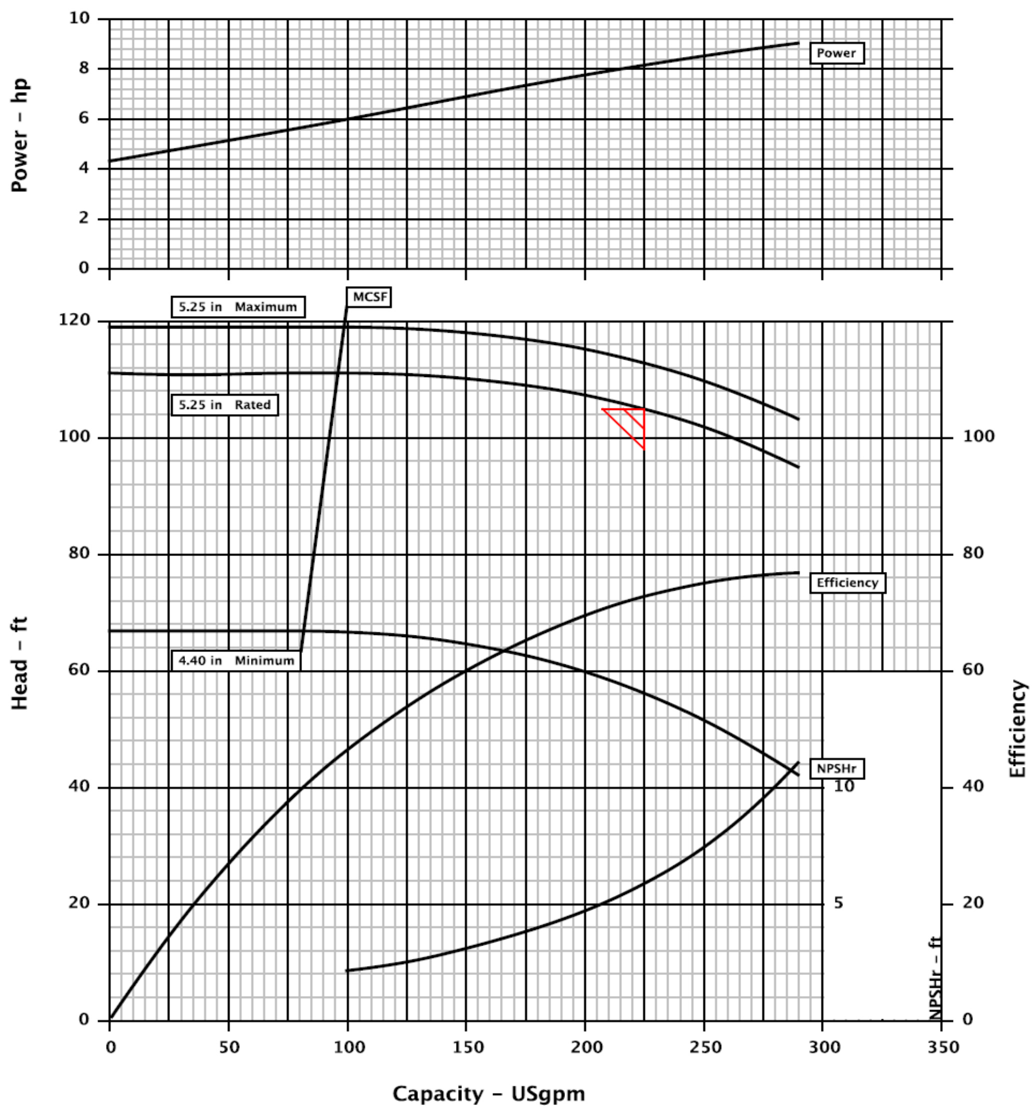
B.1: Worthington D-824 Constant Speed Centrifugal Pump [46]

FLOWSERVE

Pump size & type	: D824-3X2X5F-IND
Based on curve no.	: A-19446
Number of stages	: 1

Customer	: University of Kansas	Capacity	: 225.0 USgpm
Item number	: -	Head	: 105.00 ft
Service	:	Specific gravity	: 1.000
Flowserve reference	: Default 0.1	Pump speed	: 3550 rpm
Date	: June 13, 2013	Test tolerance	: Hydraulic Institute Level B

CURVES ARE APPROXIMATE, PUMP IS GUARANTEED FOR ONE SET OF CONDITIONS; CAPACITY, HEAD, AND EFFICIENCY.



FlowSelex v2.2

FLOWSERVE

Hydraulic Datasheet

Customer	: University of Kansas	Pump / Stages	: D824-3X2X5F-IND / 1
Customer reference	: Default	Based on curve no.	: A-19446
Item number	: -	Flowserve reference	: Default 0.1
Service	:	Date	: June 13, 2013

Operating Conditions

Capacity	: 225.0 USgpm
Water capacity (CQ=1.00)	: -
Normal capacity	: -
Total Developed Head	: 105.00 ft
Water head (CH=1.00)	: -
NPSH available (NPSHa)	: Ample
NPSHa less NPSH margin	: -
Maximum suction pressure	: 0.0 psig

Materials / Specification

Material column code	: STD
Pump specification	: General Industrial

Other Requirements

Hydraulic selection : No specification
Construction : No specification
Test tolerance : Hydraulic Institute Level B
Driver Sizing : Max Power(MCSF to EOC)with SF

Liquid

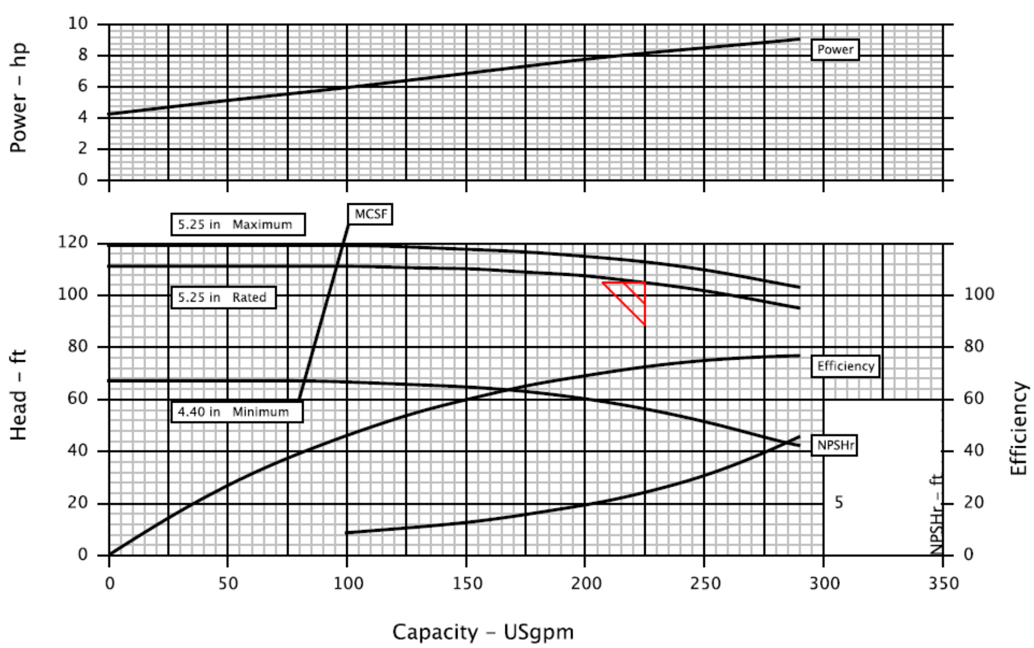
Liquid type	: Other	
Temperature / Spec. Gravity	: 60 F	/ 1.000
Solid Size - Actual / Limit	: -	/ 0.50 in
Viscosity / Vapor pressure	: 1.0 cSt	/ -

Performance

Hydraulic power	: 5.97 hp
Pump speed	: 3550 rpm
Efficiency (CE=1.00)	: 72.8 %
NPSH required (NPSHr)	: 5.7 ft
Rated power	: 8.19 hp
Maximum power	: 9.05 hp
Driver power	: 10.00 hp / 7.46 kW
Casing working pressure	: 48.0 psig
(based on shut off and Rated specific gravity @ Cut dia)	
Maximum allowable	: 175.0 psig
Hydrostatic test pressure	: 265.0 psig
Est. rated seal chamb. press.	: -

Impeller diameter	
Rated	: 5.25 in
Maximum	: 5.25 in
Minimum	: 4.40 in
Suction specific speed	: 10110 US units
Minimum continuous flow	: 98.3 USgpm
Maximum head @ rated dia	: 110.99 ft
Flow at BEP	: 290.4 USgpm
Flow as % of BEP	: 77.5 %
Efficiency at normal flow	: -
Impeller dia ratio (rated/max)	: 100.0 %
Head rise to shut off	: 5.7 %
Total head ratio (rated/max)	: 92.9 %

CURVES ARE APPROXIMATE, PUMP IS GUARANTEED FOR ONE SET OF CONDITIONS; CAPACITY, HEAD, AND EFFICIENCY.



 FlowSelex v2.2

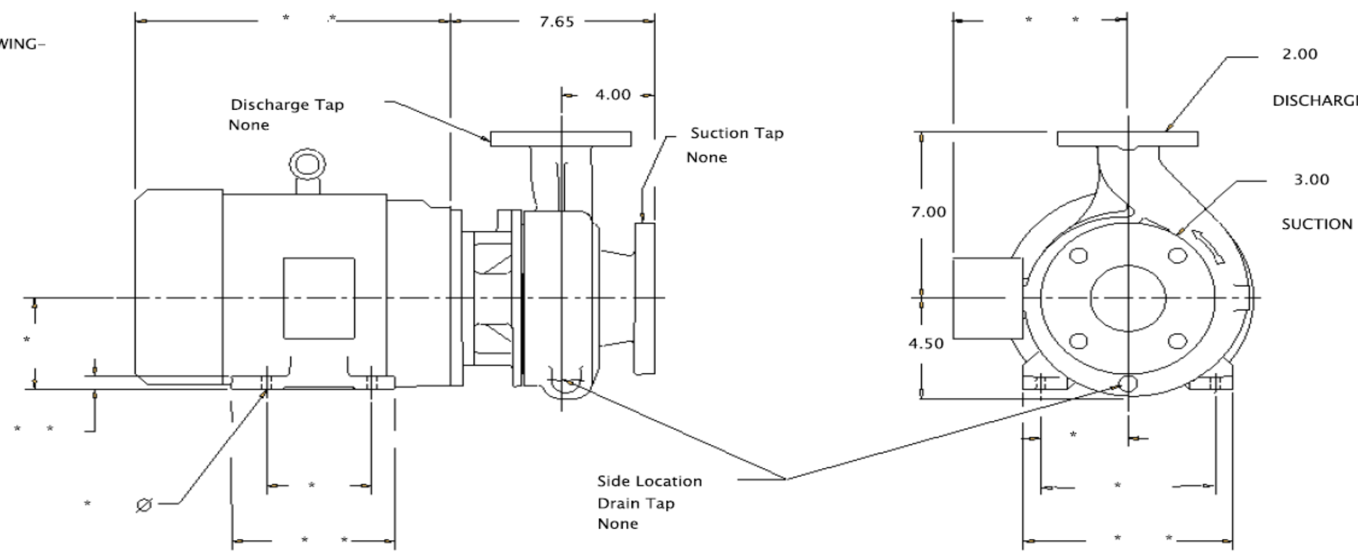
Full Page GA Drawing

Dimensions certified for construction when properly endorsed below.
Refer to factory for any "*" dimensions.

NOTES:

1. Consult pump I.O.M. before installing the pump.
2. Installation dimensions are +/- .13" (3mm), unless otherwise noted.
3. Foundation bolts and piping should not be set rigidly before receipt of equipment.
4. Motor dimensions marked (*) vary according to manufacturer and enclosure.
5. All holes in flanges straddle centerlines.
6. Piping, foundations, and systems are the responsibility of others. Flowserve Pump Division data and comments are offered as an aid, but Flowserve Pump Division cannot assume responsibility for the system design or operation. It is recommended that a specialist skilled in this area be consulted to ensure a successful installation.

-DO NOT SCALE DRAWING-



All dimensions are in inches unless otherwise specified

Customer	: University of Kansas	Pump size & type	: D824-3X2X5F-IND	Drawing number	: -
Item number	: -	Pump speed / Stages	: 3550 rpm / 1	Date	: June 13, 2013
Service	:	Flow / Head	: 225.0 USgpm / 105.00 ft	Certified by / Date :	: -
Customer PO #	: -	Driver power / Frame	: 10.00 hp / 7.46 kW /	Seal type	: -
Flowserve reference	: Default 0.1	Volts / Phase / Hz	: - / 3 / 60	Seal flush plan	: None

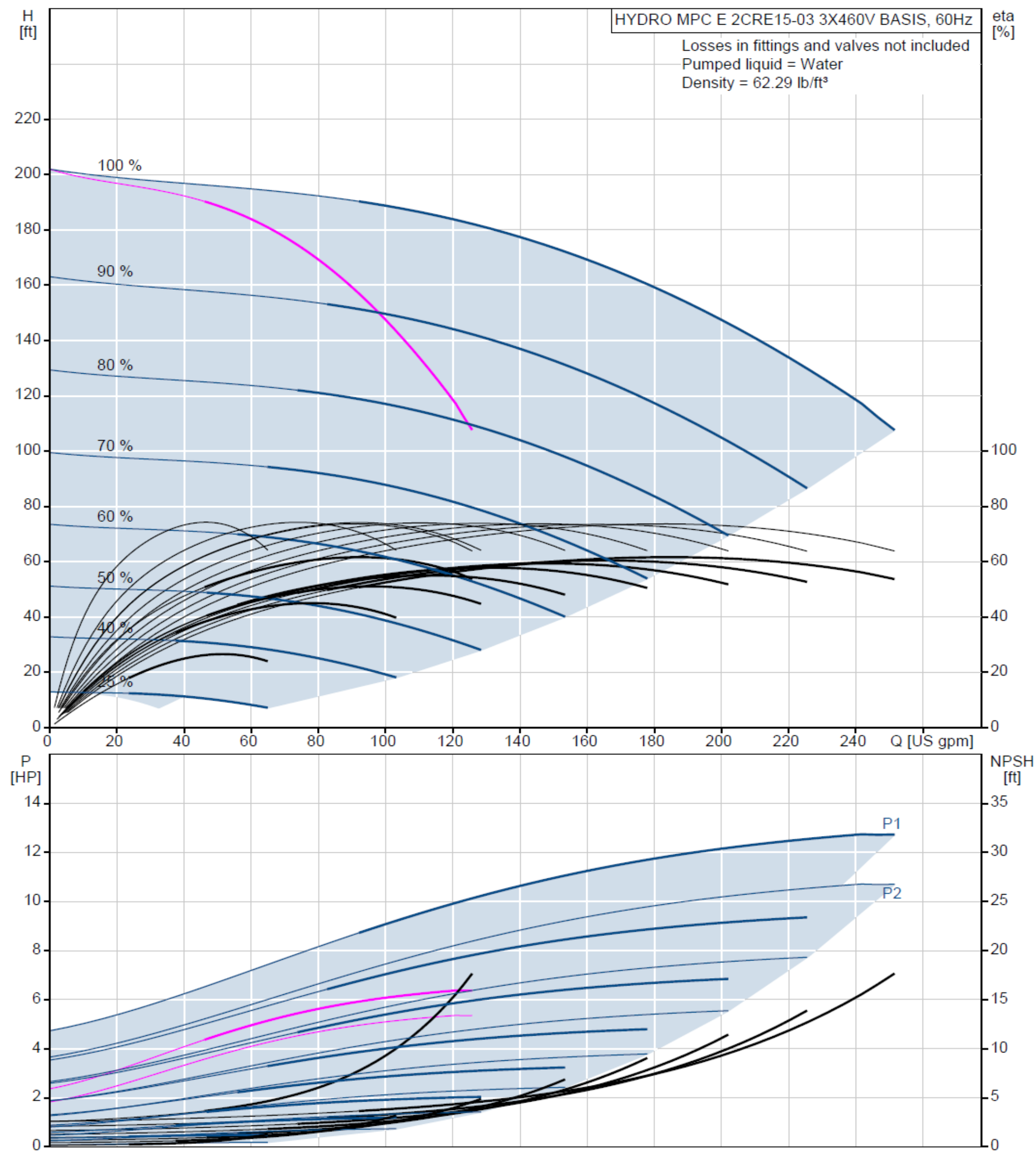
FlowSelex v2.2

B.2: Grundfos BoosterpaQ® HYDRO MPC E 2CRE 15-3 Variable Speed Pump Curve and Specifications [41]

GRUNDFOS®

Company name: The University Of Kansas
Created by: -
Phone: -
Fax: -
Date: -

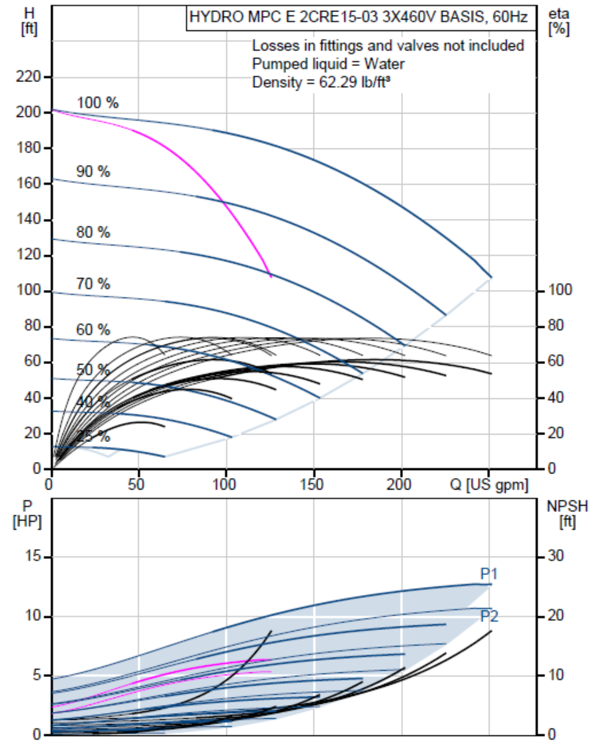
95055132 HYDRO MPC E 2CRE15-03 3X460V BASIS 60 Hz

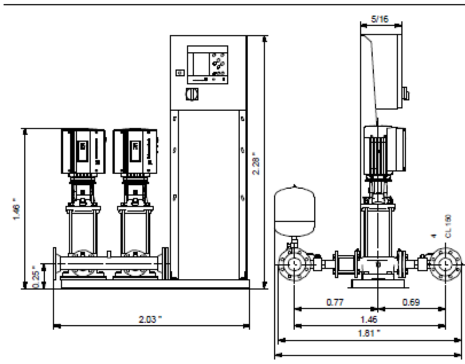


Printed from Grundfos CAPS [2013.06.034] GRUNDFOS 1/3

Company name:	The University Of Kansas
Created by:	-
Phone:	-
Fax:	-
Date:	-

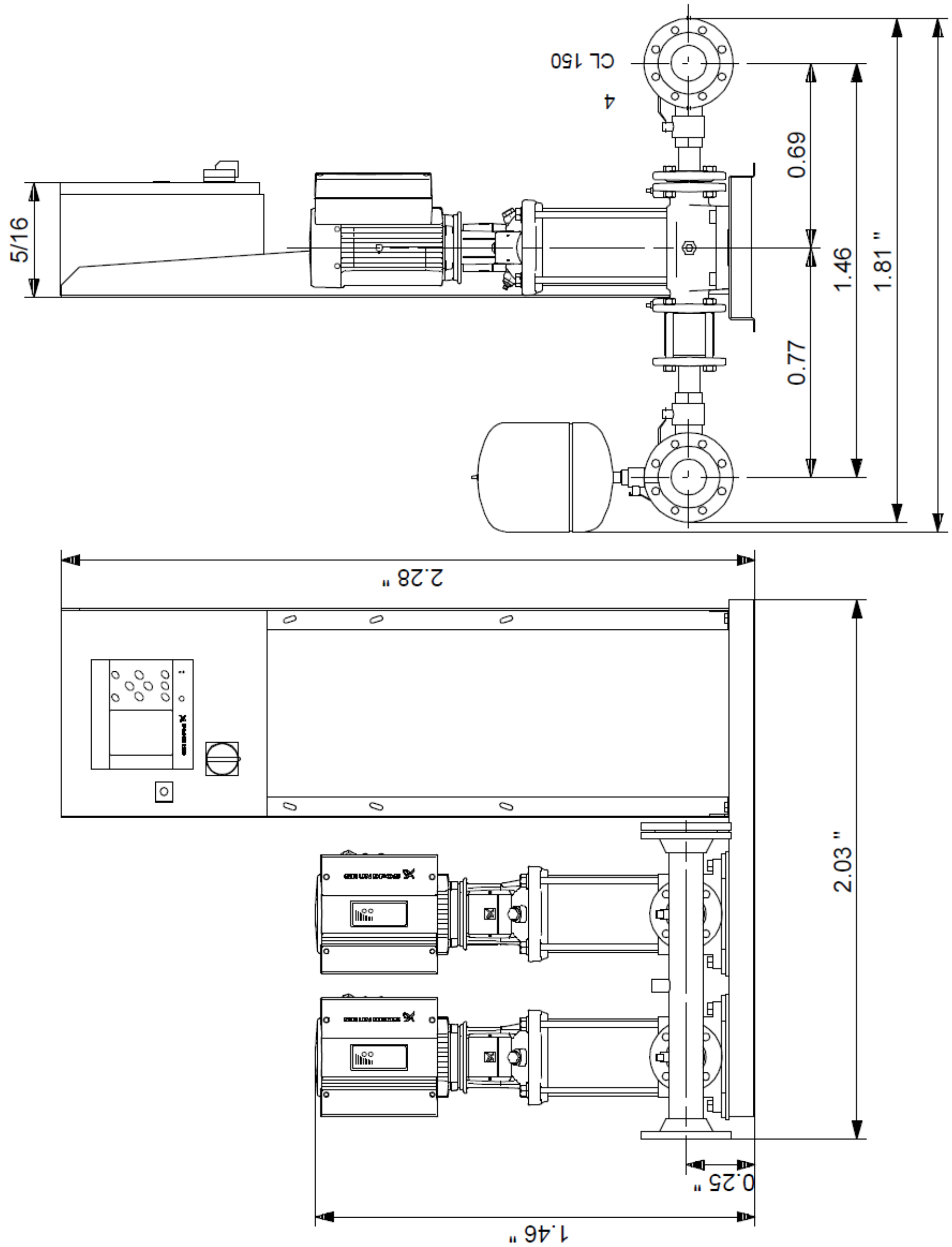
Description	Value
Product name:	HYDRO MPC E 2CRE15-03 3X460V BASIS
Product Number:	95055132
EAN number:	5700836977051
Technical:	
Max flow:	244 US gpm
Max flow system:	244 US gpm
Head max:	200 ft
Impellers main:	3
Main pump name:	CRE15-03
Main pump Number:	96541270
Number of pumps:	2
Non-ret. valve:	at discharge side
Installation:	
Maximum operating pressure:	232 psi
Maximum inlet pressure:	145 psi
Flange standard:	ANSI
Pump inlet:	4
Pump outlet:	4
Pressure stage:	CL 150
Liquid:	
Pumped liquid:	0
Liquid temperature range:	32 .. 140 °F
Liquid temp:	68 °F
Density:	62.29 lb/ft³
Kinematic viscosity:	1 cSt
Electrical data:	
Power (P2) main pump:	4.96 HP
Main frequency:	60 Hz
Rated voltage:	3 x 3X460-480V, 60 Hz
Starting main:	electronically
Rated current of system:	15 A
Enclosure class (IEC 34-5):	NEMA 4
Controls:	
Control type:	E
Operation unit:	CU 351
Tank:	
Diaphragm tank:	No
Others:	
Net weight:	589 lb
Language:	EN
Product range:	NAMREG
Configuration file Hydro MPC:	98272054





Company name:	The University Of Kansas
Created by:	-
Phone:	-
Fax:	-
Date:	-

95055132 HYDRO MPC E 2CRE15-03 3X460V BASIS 60 Hz



Note! All units are in [mm] unless others are stated.
Disclaimer: This simplified dimensional drawing does not show all details.

Appendix C: Specifications of the Instruments Used in the Project

List of All Equipment Used in the Project	
1	HOBO H12-006 Data Logger
2	Mastech HY3003D Power Supply
3	Danfoss Pressure Transducer
4	Grundfos Differential Pressure Sensor
5	Siemens Flow meter and Transmitter
6	Veris Power Monitoring Transducers
7	SureSite® Level Transducer and Visual Indicator

C.1: HOBO H12-006 Data Logger [Reproduced from Ref. 27]

onset®
HOBO® Data Loggers

HOBO® U12 Logger

Multi-channel energy & environmental monitoring

HOBO U12 data loggers provide flexibility for monitoring up to 4 channels of energy and environmental data with a single, compact logger. They provide 12-bit resolution measurements for detecting greater variability in recorded data, direct USB connectivity for convenient, fast data offload, and a 43K measurement capacity.

Supported Measurements: Temperature, Relative Humidity, Dew Point, 4-20mA, AC Current, AC Voltage, Air Velocity, Carbon Dioxide, Compressed Air Flow, DC Current, DC Voltage, Gauge Pressure, Kilowatts, Light Intensity, Volatile Organic Compound (some sensors sold separately)

Key Advantages:

- Records up to 4 channels
- Your choice of three models, with flexible measurement options
- Programmable as well as push-button start
- Compatible with a broad range of external sensors

Minimum System Requirements:

For complete information and accessories, please visit: **www.onsetcomp.com**

Part number	U12-006 (4 Ext)	U12-012 (Temp/RH/Light/Ext)	U12-013 (Temp/RH/2 Ext)
Memory	43,000 measurements		
Sampling rate	1 second to 18 hours, user-selectable		
Battery life	1 year typical, user-replaceable, CR2032		
		Temperature	
Max range		-20° to 70°C (-4° to 158°F)	
Accuracy		± 0.35°C from 0° to 50°C (± 0.63°F from 32° to 122°F)	
Resolution (12-bit)		0.03°C @ 25°C (0.05°F @ 77°F)	
		Relative Humidity	
Measurement range		5% to 95% RH (non-condensing)	
Accuracy		± 2.5% typical, 3.5% maximum, from 10 to 90% RH	
Resolution (10-bit)		0.03% RH	
		Light Intensity	
		Designed for general purpose indoor measurement of relative light levels	
Range		1 to 3000 footcandles (lumens/ft2) typical 0-32,300 lumens/m2	
	External Input		
Range	0 to 2.5 VDC		
Accuracy	± 2 mV, ± 2.5% of absolute reading		
Resolution	0.6 mV		
CE compliant	Yes		

*USB cable included with software

For stand-alone data logging applications in harsh indoor environments, see the 4-channel HOBO U12 Industrial data logger (U12-008) at onsetcomp.com

Contact Us

Sales (8am to 5pm ET, Monday through Friday)
- Email sales@onsetcomp.com
- Call 1-800-564-4377
- Fax 508-759-9100

Technical Support
- (8am to 8pm ET, Monday through Friday)
- Contact Product Support
- Call 877-564-4377

C.2: Mastech HY3003D Power Supply [Reproduced from Ref. 44]

Power Supply *HY30XX Series*

MODEL EXPLAINATION:

HY XX XX X - X

① ② ③ ④ ⑤

① Products of MASTEC

② Output voltage numbers

③ Output current numbers

④ no: LED display

D: LCD display

C: two pointer meters display

S: four pointer meters display

⑤ no: single output voltage current regulated

2: double output voltage current regulated

3: double output voltage current regulated + fixed 5V3A

MODEM	HY3002D	HY3003D	HY3005D
Input Voltage	110/220V±10%		
Output Voltage	0 ~ 30V		
Output Current	0 ~2A	0 ~ 3A	0 ~ 5A
Source Effect	CV ≤ 0.01%±1mV; CC ≤ 0.02%±1mA		
Load Effect	CV ≤ 0.01%±5mV; CC ≤ 0.02%±5mA		
Ripple & Noise	≤ 1mVrms		
Display	Two 3 1/2 digit LCD display		
Accuracy	V: ±1%±2digits; C: ±2%±2digits		
Size	291 x 158 x 136mm		
Weight	3 ~ 6kg		

MODEM	HY3002C	HY3003C	HY3005C
Input Voltage	110/220V ± 10%AC		
Output Voltage	0 ~ 30V		
Output Current	0 ~ 2A	0 ~ 3A	0 ~ 5A
Source Effect	CV≤ 0.01%±1mV; CC≤ 0.02%±1mA		
Load Effect	CV≤ 0.01%±5mV; CC≤ 0.02%±5mA		
Ripple & Noise	≤ 1mVrms		
Display	Voltage & Amperometer display		
Accuracy	2.5%f.s.		
Size	291 x 158 x 136mm		
Weight	3 ~ 6kg		

Sinotech Shanghai
Room 1404, 1759 North Zhongshan Road, Putuo District,
Shanghai, China

Page 1

C.3: Danfoss Pressure Transducer [Reproduced from Ref. 37]

Data sheet

Pressure transmitter for general industrial purposes Type MBS 3000 and MBS 3050

The compact pressure transmitter, type MBS 3000, is designed for use in almost all industrial applications, and offers a reliable pressure measurement, even under harsh environmental conditions.

The compact heavy duty pressure transmitter MBS 3050 with integrated pulse-snubber is designed for use in hydraulic applications with severe medium influences like cavitation, liquid hammer or pressure peaks and offers a reliable pressure measurement, even under harsh environmental conditions.

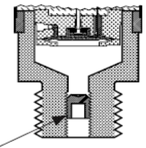
The flexible pressure transmitter programme covers different output signals, absolute or gauge (relative) versions, measuring ranges from 0 – 1 to 0 – 600 bar.
A wide range of pressure and electrical connections are available.

Excellent vibration stability, robust construction, and a high degree of EMC/EMI protection equip the pressure transmitter to meet the most stringent industrial requirements.

Features

- Designed for use in severe industrial and hydraulic environments
- Resistant to cavitation, liquid hammer and pressure peaks (MBS 3050)
- Enslosure and wetted parts of acid-resistant stainless steel (AISI 316L)
- Pressure ranges in relative (gauge) or absolute from 0 up to 600 bar
- All standard output signals: 4 – 20 mA, 0 – 5 V, 1 – 5 V, 1 – 6 V, 0 – 10 V, 1 – 10 V
- A wide range of pressure and electrical connections
- Temperature compensated and laser calibrated
- For use in zone 2 explosive atmospheres

Application and media conditions for MBS 3050



Application

Cavitation, liquid hammer and pressure peaks may occur in hydraulic systems with changes in flow velocity, e.g. fast closing of a valve or pump starts and stops.

The problem may occur on the inlet and outlet side, even at rather low operating pressures.

Media condition

Clogging of the nozzle may occur in liquids containing particles. Mounting the transmitter in an upright position minimizes the risk of clogging, because the flow in the nozzle is limited to the start-up period until the dead volume behind the nozzle orifice is filled. The media viscosity has only little effect on the response time. Even at a viscosities up to 100 cSt, the response time will not exceed 4 ms.

Technical data

Performance (EN 60770)

Accuracy (incl. non-linearity, hysteresis and repeatability)		≤ ± 0.5% FS (typ.)
		≤ ± 1% FS (max.)
Non-linearity BFSL (conformity)		≤ ± 0.2% FS
Hysteresis and repeatability		≤ ± 0.1% FS
Thermal zero point shift		≤ ± 0.1% FS / 10K (typ.)
		≤ ± 0.2% FS / 10K (max.)
Thermal sensitivity (span) shift		≤ ± 0.1% FS / 10K (typ.)
		≤ ± 0.2% FS / 10K (max.)
Response time	Liquids with viscosity < 100 cSt	< 4 ms
	Air and gases (MBS 3050)	< 35 ms
Overload pressure (static)		6 × FS (max. 1500 bar)
Burst pressure		6 × FS (max. 2000 bar)
Durability, P: 10 – 90% FS		>10 × 10^6 cycles

Electrical specifications

Nom. output signal (short-circuit protected)	4 – 20 mA	0 – 5, 1 – 5, 1 – 6 V	0 – 10 V, 1 – 10 V
Supply voltage [U_B], polarity protected	9 – 32 V	9 – 30 V	15 – 30 V
Supply – current consumption	–	≤ 5 mA	≤ 8 mA
Supply voltage dependency	≤ ± 0.1% FS / 10 V		
Current limitation	28 mA (typ.)	–	
Output impedance	–	≥ 25 kΩ	
Load [R_L] (load connected to 0 V)	R_L ≤ (U_B-9V) / 0.02 A	R_L ≥ 10 kΩ	R_L ≥ 15 kΩ

Technical data
(continued)

Environmental conditions

Sensor temperature range			-40 – 85 °C
Media temperature range			115 - (0.35 × Ambient temp.)
Ambient temperature range (depending on electrical connection)			See page 6
Compensated temperature range			0 – 80 °C
Transport/storage temperature range			-50 – 85 °C
EMC – Emission			EN 61000-6-3
EMC – Immunity			EN 61000-6-2
Insulation resistance			> 100 MΩ at 100 V
Mains frequency test			Based on SEN 361503
Vibration stability	Sinusoidal	15.9 mm-pp, 5 Hz – 25 Hz	IEC 60068-2-6
		20 g, 25 Hz – 2 kHz	
	Random	7.5 g_{rms}, 5 Hz – 1 kHz	IEC 60068-2-64
Shock resistance	Shock	500 g / 1 ms	IEC 60068-2-27
	Free fall	1 m	IEC 60068-2-32
Enclosure (depending on electrical connection)			See page 6

Explosive atmospheres

Zone 2 applications	CE Ex II 3G Ex nA IIC T3 Gc -40C<Ta<+85C	EN60079-0; EN60079-15

Mechanical characteristics

Materials	Wetted parts	EN 10088-1; 1.4404 (AISI 316 L)
	Enclosure	EN 10088-1; 1.4404 (AISI 316 L)
	Electrical connections	See page 6
Net weight (depending on pressure connection and electrical connection)		0.2 – 0.3 kg

C.4: Grundfos Differential Pressure Sensor [Reproduced from Ref. 38]

GRUNDFOS **DATA SHEET**

DPI 0 - 2.5

Differential Pressuresensor, Industry, 0 - 2.5 bar

TM04 4738 1909

Fig. 1 DPI sensor

Technical overview

Grundfos Direct Sensors ™ , type DPI, is a series of differential pressure sensors for industry. The DPI sensors are compatible with wet, aggressive media and are available for differential pressure ranges of 0 - 0.6 up to 0 - 10 bar.

The DPI sensor utilises MEMS sensing technology in combination with a novel packaging concept using corrosion-resistant coating on the MEMS sensing element. This makes the DPI sensor very robust and ideal for pump integration and monitoring in harsh environments.

Applications

- Pump and pump control systems
- Filters (monitoring)
- Cooling and temperature control systems
- Water treatment systems
- Boiler control systems
- Renewable energy systems
- Heat exchanger efficiency (monitoring of fouling).

Features

- Pressure ranges: 0 - 0.6; 0 - 1; 0 - 1.2; 0 - 1.6; 0 - 2.5; 0 - 4; 0 - 6 and 0 - 10 bar differential pressure
- Designed for harsh environments
- Analogue output signal
- Compact and well proven design
- MEMS sensing technology
- Approved for the EU, US and Canadian markets.

Benefits

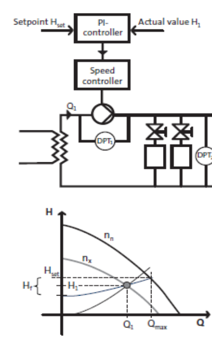
- Compatible with wet, aggressive media
- Accurate, linearised output signal
- Cost-effective and robust design.

Specifications

Pressure	
Measuring range (differential)	2.5 bar
Accuracy (IEC 61298-2)	2 % FS
Response time	< 0.5 s
Static Pressure P_1	16 bar
Static Pressure P_2	10 bar
Max system pressure	16 bar
Media and environment	
Media	Liquids, gasses and air
Media temperature (operation)	–10 to +70 °C
Media temperature (peak)	up to +80 °C
Ambient air temperature	–40 to +70 °C
Ambient air temperature (peak)	–55 to +90 °C
Humidity	0 to 95 % (relative), non-condensing
System burst pressure	25 bar
Electrical data	
Power supply	12-30 VDC
Output signals	4-20 mA
Load impedance	24 V max. 500 kΩ 16 V max. 200 kΩ 12 V max. 100 kΩ
Sensor materials	
Sensing element	Silicon-based MEMS sensor
Seal	FKM rubber
Housing	DIN W.-Nr. 1.4305
Wetted materials	FKM and PPS
Environmental standards	
Enclosure class	IP55
Temperature cycling	IEC 68-2-14
Vibration (non-destructive)	20 to 2000 Hz, 10G, 4h
Immunity	EN 61000-6-2
Emission	EN 61000-6-3
Weight	550 g

Flow compensated differential pressure control

(SPR Reglung)



TM03 0411 5004

Fig. 2 SPR Reglung

If the equipment is used in a manner not specified by the manufacturer, the protection provided by the equipment may be impaired.

BE > THINK > INNOVATE >

GRUNDFOS

Dimensions [mm]

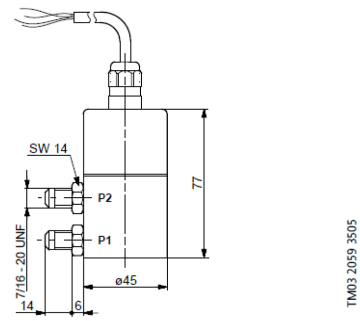


Fig. 3 Dimensional sketch

Output signals

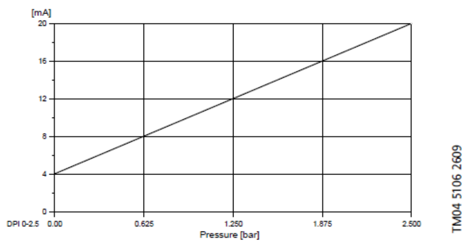


Fig. 4 Differential pressure response

Electrical connections

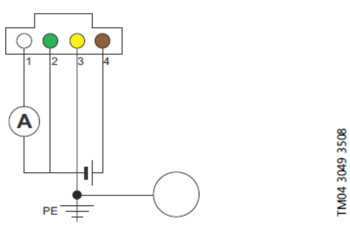


Fig. 5 Electrical connections

Pin configuration		Colour
1	Test conductor (can be cut off during mounting). Do not connect this conductor to the voltage supply.	White
2	Signal conductor	Green
3	GND (earth conductor)	Yellow
4	12-30 V supply voltage	Brown

96985463 1109	GB

Sensor Interface type SI 001 PSU

Power supply and amplifier for cables above 30 m and 2 wire connection of 400 VAC

Fig. 6 Sensor Interface, SI 001 PSU

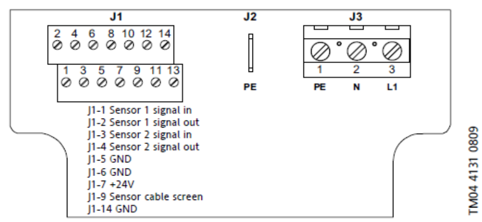


Fig. 7 Connections for power supply / amplifier

Part
Sensor Interface, SI 001 PSU

Accessories

Pos.	Component		
A	Fitting 6 mm	AISI 316	Tube connection
	Fitting 8 mm		
	Fitting 6 mm		Cutting ring
	Fitting 8 mm		
B	Cable for DPI 5.0 m		
	Cable for DPI 10.0 m		
	Wall bracket for sensor		

Type key

The DPI sensor is labelled with a type designation.

96573683 - XX - XXX XXXXX

Product number	96573683
Version	XX
Production year and week	XXX
Consecutive number	XXXXX

For more information, see http://www.grundfos.com/directsensors.

Subject to alterations.

Grundfos Sensor A/S
Poul Due Jensens Vej 7. DK-8850 Bjerringbro. Denmark
Telephone: +45 87 50 14 00

www.grundfos.com\directsensors

GRUNDFOS

C.5: Siemens Flow Meter and Transmitter [Reproduced from Ref. 36]

The SITRANS F M MAG 5100 W with its patented liners of hard rubber NBR or ebonite and EPDM is a sensor for all water applications such as ground water, drinking water, cooling water, waste water, sewage or sludge applications. Application examples: Water abstraction, Water distribution network, Waste water and as custody transfer water meter or cooling meter.

Details

Measuring range	0 to 10 m/s
Nominal Sizes	From DN 15 to DN 2000 (1" to 78")
Accuracy	0.2 % ±2.5 mm/s
Operating Pressure	Max. 16 bar (Max. 150 psi)
Ambient temperature	From -40 to 70 °C (-40 to 158 °F)
Medium Temperature	From -10 to 70 °C (14 to 158 °F)
Liners	EPDM NBR hard rubber Ebonite hard rubber
Electrodes	Hastelloy C-276 Built-in grounding electrodes
Material	Carbon steel, with corrosion resistant two-component epoxy coating
Drinking Water Approvals	EPDM: WRAS, NSF/ANSI Standard 61, DVGW 270, ACS and BelgAqua NBR: NSF/ANSI Standard 61, WRAS Ebonite: WRAS
Custody Transfer Approvals	OILM R 49 MI-001 PTB K7.2 (Germany) BEV OE12/C040 (Austria)
General approval	MCERTS Sira Certificate No. MC080136/00

The SITRANS F M MAG 5000 is a microprocessor-based transmitter engineered for high performance, easy installation, commissioning and maintenance. The transmitter is truly robust, cost-effective and suitable for all-round applications and has a measuring accuracy of ± 0.4% of the flow rate (incl. sensor).

Application Examples: Water and waste water, General process industry, Food & beverage industry

Details

Accuracy	0.4 % ±1 mm/s
Input / output	1 current output 1 digital output 1 relay output
Communication	HART
Display	Background illumination with alphanumeric text, 3 x 20 characters
Enclosure	IP67 (NEMA 4x/6) IP20 (NEMA 2)
Power supply	12-24 V a.c./d.c. 115-230 V a.c.
Ambient temperature	From -20 to 50 °C (-4 to 122 °F)
Approvals	MI-001 Danak PTB OIML R49
Ex-approvals	FM/CSA Class 1, Div 2

C.6: Veris Power Monitoring Transducers [Reproduced from Ref. 39]

Enercept® kW/kWh Transducers (4-20mA or Pulse Output)

Integral Submetering Solution Eliminates the Need for Separate Enclosures

H804x/H805x

Patent #6,373,238

POWER/ENERGY MONITORING

DESCRIPTION

The **Enercept H804x and H805x Series** kW (real power)/kWh (consumption) transducers combine processing electronics and industrial grade CTs in an easy-to-install split-core package. These devices continuously measure voltage and current values for the monitored conductors and update calculations to provide highly accurate true RMS power readings. Models designed for balanced loads include one CT only, while models for unbalanced loads have three CTs.

The unique design of the H804x/H805x Series transducers reduces the number of installed components, making them ideal for monitoring electrical power in commercial and industrial facilities The H804x provides industry-standard 4-20mA output, and the H805x provides a pulse output.

Installation is simple. The H804x/H805x eliminates the need to mount and wire a transducer and enclosure. CTs and voltage leads are color-matched, and the meters are designed to detect and automatically compensate for phase reversal. No more worries about CT load orientation.

FEATURES

- Revenue Grade measurements
- Fast split-core installation eliminates the need to remove conductors... perfect for retrofits
- Precision meter electronics and current transformers in a single package... reduces the number of installed components...creating significant labor savings
- Smart electronics eliminate the need to be concerned with CT orientation... fast trouble-free installation

APPLICATIONS

- Optimize chillers, pumps & cooling towers
- Energy management & performance contracting
- Control processes
- Activity-based costing in commercial and industrial facilities
- Monitor real-time power
- Load shedding

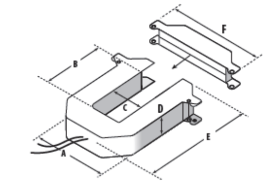
SPECIFICATIONS

5 Year Warranty

Inputs:	
Voltage Input	208/240 or 480VAC, 50/60 Hz RMS [1,2,3]
Current Input	Up to 2400A continuous per phase [2,3]
Accuracy:	
System Accuracy	±1% of reading from 10% to 100% of the rated current of the CTs, accomplished by matching the CTs with electronics and calibrating them as a system
Outputs:	
H804x	
Output	4-20mA
Supply Power (current loop)	9-30VDC, 30mA max.
H805x	
Pulsed Output	Field selectable; 1, 0.5, 0.25, 0.1kWh/pulse [4]
Pulsed Output Type	Normally Open, Opto-FET, 100mA@24VDC
Environmental:	
Operating Temperature Range	0° to 60°C (32° F to 140°F), 50°C (122°F) for 2400A
Humidity Range	0 - 95% noncondensing
Agency Approvals	UL508

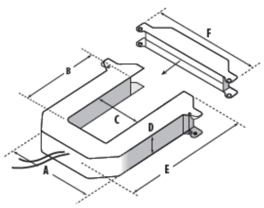
[1] Do not install on the line or load side of a VFD unit, or on any other equipment generating harmonics. For line side applications, use the E5x Series meters.
[2] Contact factory to interface with voltages above 480VAC or current above 2400 Amps.
[3] Do not apply 600V Class current transformers to circuits having a phase-to-phase voltage greater than 600V, unless adequate additional insulation is applied between the primary conductor and the current transformers. Veris assumes no responsibility for damage of equipment or personal injury caused by products operated on circuits above their published ratings.
[4] Count must be multiplied by the number of phases when using single CT models to monitor balanced multiphase systems.

DIMENSIONAL DRAWINGS



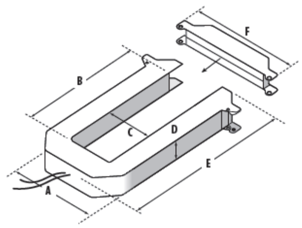
SMALL
100/300 Amp

A = 3.8" (96 mm)
B = 1.2" (30 mm)
C = 1.3" (31 mm)
D = 1.2" (30 mm)
E = 4.0" (100 mm)
F = 4.8" (121 mm)



MEDIUM
400/800 Amp

A = 4.9" (125 mm)
B = 2.9" (73 mm)
C = 2.5" (62 mm)
D = 1.2" (30 mm)
E = 5.2" (132 mm)
F = 6.0" (151 mm)

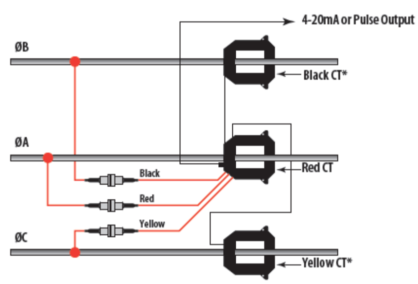


LARGE
800/1600/2400 Amp

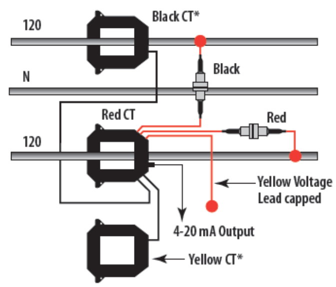
A = 4.9" (125 mm)
B = 5.5" (139 mm)
C = 2.5" (62 mm)
D = 1.2" (30 mm)
E = 7.9" (201 mm)
F = 6.0" (151 mm)

APPLICATION/WIRING EXAMPLES

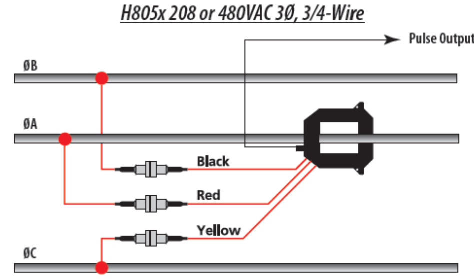
H804x/H805x 208 or 480VAC 3Ø, 3/4 Wire



H804x 240VAC 1Ø, 3-Wire



H805x 208 or 480VAC 3Ø, 3/4-Wire



ORDERING INFORMATION

c UL us LISTED

4-20 mA Output Power Transducers

Single CT Models for Use with Balanced 3Ø Loads
Three CT Models for Use with Unbalanced 3Ø Loads

MODEL	VOLTAGE	MAX. AMPS	OUTPUT	CT SIZE	CT TYPE
H8041-0100-2	208/240	100	4-20mA	SMALL	Single CT Model
H8041-0300-2		300		SMALL	
H8041-0400-3		400		MEDIUM	
H8041-0800-3		800		MEDIUM	
H8041-0800-4		800		LARGE	
H8041-1600-4		1600		LARGE	
H8041-2400-4		2400		LARGE	
H8042-0100-2	480	100		SMALL	Single CT Model
H8042-0300-2		300		SMALL	
H8042-0400-3		400		MEDIUM	
H8042-0800-3		800		MEDIUM	
H8042-0800-4		800		LARGE	
H8042-1600-4		1600		LARGE	
H8042-2400-4		2400		LARGE	
H8043-0100-2	208/240	100		SMALL	Three CT Model
H8043-0300-2		300		SMALL	
H8043-0400-3		400		MEDIUM	
H8043-0800-3		800		MEDIUM	
H8043-0800-4		800		LARGE	
H8043-1600-4		1600		LARGE	
H8043-2400-4		2400		LARGE	
H8044-0100-2	480	100	4-20mA	SMALL	Three CT Model
H8044-0300-2		300		SMALL	
H8044-0400-3		400		MEDIUM	
H8044-0800-3		800		MEDIUM	
H8044-0800-4		800		LARGE	
H8044-1600-4		1600		LARGE	
H8044-2400-4		2400		LARGE	

Pulse Output Power Transducers

Single CT Models for Use with Balanced 3Ø Loads
Three CT Models for Use with Unbalanced 3Ø Loads

MODEL	VOLTAGE	MAX. AMPS	OUTPUT	CT SIZE	CT TYPE
H8051-0100-2	208/480	100	Pulse	SMALL	Single CT Model
H8051-0300-2		300		SMALL	
H8051-0400-3		400		MEDIUM	
H8051-0800-3		800		MEDIUM	
H8051-0800-4		800		LARGE	
H8051-1600-4		1600		LARGE	
H8051-2400-4		2400		LARGE	
H8053-0100-2		100		SMALL	Three CT Model
H8053-0300-2		300		SMALL	
H8053-0400-3		400		MEDIUM	
H8053-0800-3		800		MEDIUM	
H8053-0800-4		800		LARGE	
H8053-1600-4		1600		LARGE	
H8053-2400-4		2400		LARGE	

ACCESSORIES

CT Mounting brackets (AH06)

POWER/ENERGY MONITORING

HQ0001811.C 01131

C.7: SureSite® Level Transducer and Visual Indicator [Reproduced from Ref. 29]

Gems Sensors & Controls

Alloy Versions–Miniature Size

ORDER IT! Ordering is Easy! See Page D-6. Easy online ordering too!

- Lengths to over 20 feet (6.1 meters)
- 316 Stainless Steel construction
- Pressures to 400 PSI (27 bar) – Temperature to 400°F (204°C)

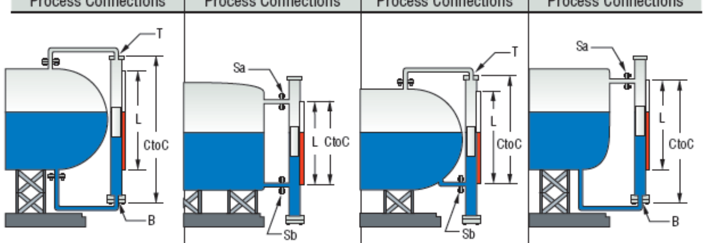
Use these Mini SureSite Indicators where space is tight—they feature a diameter of only 1-1/4˝! They can replace existing, antiquated sightglasses for excellent external, visual liquid level indication. Mini SureSite Indicators are ideal for use with clean, low viscosity liquids.

Typical Applications

- Pharmaceuticals
- Medical Equipment
- Food and Beverages
- Semiconductor Manufacturing
- Boilers

1. Mounting Configuration Types

L = Length of Visual Indication

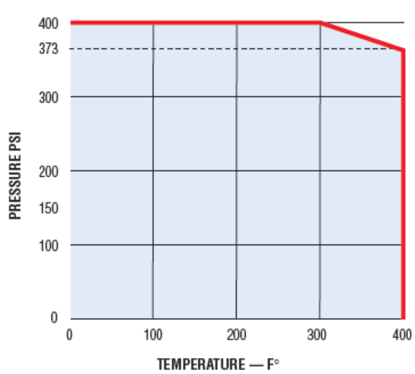


	Type AM	Type BM	Type CM	Type DM
	Top and Bottom Process Connections	**Side and Side** Process Connections	**Top and Side** Process Connections	**Side and Bottom** Process Connections
Typical Lengths*	C to C = L + 7.72˝ (196 mm)	C to C = L	C to C = L + 3˝ (76 mm)	C to C = L + 5˝ (127 mm)
Flag Material	Plastic (300°F/148.9°C) or Aluminum (400°F/204°C)			
Length of Indication (Uninterrupted)	240˝ (610 cm)			

*Dimensions vary due to connections, material and specific gravity.
Note: Additional materials, floats, connections and manufacturing techniques are available to extend lengths and operational capabilities. Please contact Gems if the parameters above do not meet your requirements.

Miniature SureSite Performance

Gems configures Miniature SureSite Indicators, using various materials and fittings, to perform within the Pressure/Temperature parameters specified in the chart at right. Consult the factory with pressure/temperature requirements that fall outside the parameters shown here.



Note: SureSite Indicators are available for temperatures as low as -200°F (-129°C)

Visit www.GemsSensors.com for most current information.

2. Connection Codes

(See complete descriptions below)

	Blind		NPT				Flange		Weld	
			Fixed		Removable					
	Fixed	Removable	Female	Male	Female	Male	Fixed	Removable	Socket Butt	Removable Butt
Standard Connections	T1	T10	T2	T3	T11	T12	T19	T20	T18	T13
Sanitary Connections							T7	T8		

Blind	NPT Male	NPT Female	Flange	Sanitary Flange	Buttweld Nipple
S1	S2	S3	S4	S5	S6

— Connection Codes and Materials background-shaded in this color are stocked by Gems. Select these connections where possible to obtain the most economical SureSite Indicators with a prompt 3-day delivery.

	Blind		NPT				Flange		Weld	
			Fixed		Removable					
	Fixed	Removable	Female	Male	Female	Male	Fixed	Removable	Socket Butt	Removable Butt
Standard Connections	B1	B10	B2	B3	B11	B12	B19	B20	B18	B13
Sanitary Connections							B7	B8		

Note: Gems recommends a removable top and/or bottom connection for float access.

Connection Code Descriptions
Please provide all connections when completing the OrderIt! Product Check List (located on the following page).
Note: Before selecting your connections, consider incorporating your vent and drain requirements.

T & B (Top and Bottom)

- T/B 1. Welded cap
- T/B 2. Welded cap with FNPT
- T/B 3. Welded cap with MNPT
- T/B 7. Sanitary flange
- T/B 8. Sanitary flange with mating blind flange
- T/B 10. Standard fixed flange/mating blind flange
- T/B 11. Standard fixed flange/mating FNPT reducing flange
- T/B 12. Standard fixed flange/mating flange with MNPT nipple
- T/B 13. Standard fixed flange/mating flange with butt weld nipple
- T/B 18. Welded cap with butt weld nipple
- T/B 19. Welded cap with ANSI flange
- T/B 20. Standard fixed flange/mating reducing flange spool with ANSI flange

Sa & Sb (Sides)

- S1. No connection
- S2. MNPT nipple
- S3. FNPT coupling
- S4. ANSI flange
- S5. Sanitary flange
- S6. Buttweld nipple

3-Day Qwik Configured
Available for up to 10 units
Built & Shipped in 3 Days!

Need it quick? Choose materials and components with the color shading for 3-Day manufacturing and shipping. See the Product Configurator section at www.gemssensors.com for further details.

Accessories – Pages D-16 to D-18

Make more of your SureSite® Indicator with the productivity-enhancing accessories found at the end of this section.

- **Indicating Scales**
  Add graduations to your flag indication.
- **Switch Modules**
  Control pumps, valves, alarms, etc. Mount externally on housing for infinite positioning.
- **Continuous Output Transmitters**
  Signal conditioned for compatibility with most electronic instruments to 300°F (149°C).

Performance Notes:

1. As an option **either** the Switch Modules or Transmitter can be used on a Miniature SureSite Indicator - **Not Both.**
2. Minimum specific gravity is 0.7.
3. Standard O-ring seal material is Viton®. Others available upon request.
4. Electropolished Outer Diameter (OD) and/or Inner Diameter (ID) housings available upon request.

Appendix D: Daily Temperature Readings from All Months Considered in the Project [Reproduced from Ref. 45]

U.S. Department of Commerce
National Oceanic & Atmospheric Administration
National Environmental Satellite, Data, and Information Service

Record of Climatological Observations
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National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801
www.ncdc.noaa.gov

Station: **LAWRENCE, KS US**
Observation Time Temperature: 0700 Observation Time Precipitation: 0700

GHCND:USC00144559
Elev: 1004 ft. Lat: 38.958° N Lon: 95.251° W

Preliminary	Year	Month	Day	Temperature (°F) 24 hrs. ending at observation time Max.	Temperature (°F) 24 hrs. ending at observation time Min.	Temperature (°F) at Observation	Precipitation (see **) 24 Hour Amounts ending at observation time Rain, melted snow, etc. (in)	Flag	Snow, ice pellets, hail (in)	Flag	At Obs Time Snow, ice pellets, hail, ice on ground (in)	Evaporation 24 Hour Wind Movement (mi)	Evaporation Amount of Evap. (in)	Soil Temperature (°F) 4 in depth Ground Cover (see *)	4 in depth Max.	4 in depth Min.	8 in depth Ground Cover (see *)	8 in depth Max.	8 in depth Min.
	2012	2	1	66	32	42	0.00		0.0		0								
	2012	2	2	62	38	40	0.00		0.0		0								
	2012	2	3	62	40	44	1.15		0.0		0								
	2012	2	4	44	36	37	0.15		0.0		0								
	2012	2	5	44	31	44	0.21		0.2		0								
	2012	2	6	47	27	29	0.00		0.0		0								
	2012	2	7	51	29	39	0.00		0.0		0								
	2012	2	8	39	29	31	0.00		0.0		0								
	2012	2	9	33	30	33	T		0.0		0								
	2012	2	10	37	27	30	T		T		0								
	2012	2	11	31	12	13	0.00		0.0		0								
	2012	2	12	30	9	27	0.00		0.0		0								
	2012	2	13	37	22	30	0.20		1.8		2								
	2012	2	14	35	24	35	0.15		0.0		1								
	2012	2	15	44	32	38	0.04		0.0		T								
	2012	2	16	46	34	39	T		0.0		0								
	2012	2	17	46	24	26	0.00		0.0		0								
	2012	2	18	57	26	34	0.00		0.0		0								
	2012	2	19	47	29	30	0.00		0.0		0								
	2012	2	20	51	30	46	0.00		0.0		0								
	2012	2	21	49	34	38	0.35		0.0		0								
	2012	2	22	54	38	46	0.00		0.0		0								
	2012	2	23	63	45	51	T		0.0		0								
	2012	2	24	52	34	36	0.00		0.0		0								
	2012	2	25	48	26	30	0.00		0.0		0								
	2012	2	26	50	29	50	0.00		0.0		0								
	2012	2	27			32	0.00		0.0		0								
	2012	2	28	48	32	47	T		0.0		0								
	2012	2	29	62	42	43	1.16		0.0		0								
			Summary	47.7	30.0		3.41		2.0										

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www.ncdc.noaa.gov

Station: **LAWRENCE, KS US** GHCND:USC00144559
Observation Time Temperature: 0700 Observation Time Precipitation: 0700 Elev: 1004 ft. Lat: 38.958° N Lon: 95.251° W

Preliminary	Year	Month	Day	Temperature (°F)			Precipitation(see **)					Evaporation		Soil Temperature (°F)					
				24 hrs. ending at observation time		at Observation	24 Hour Amounts ending at observation time				At Obs Time			4 in depth			8 in depth		
				Max.	Min.		Rain, melted snow, etc. (in)	Flag	Snow, ice pellets, hail (in)	Flag	Snow, ice pellets, hail, ice on ground (in)	24 Hour Wind Movement (mi)	Amount of Evap. (in)	Ground Cover (see *)	Max.	Min.	Ground Cover (see *)	Max.	Min.
	2012	3	1	61	31	34	0.00		0.0		0								
	2012	3	2	70	33	33	0.03		T		T								
	2012	3	3	49	29	35	0.00												
	2012	3	4	56	28	49	0.00		0.0		0								
	2012	3	5	64	49	58	0.00		0.0		0								
	2012	3	6	61	53	61	0.00		0.0		0								
	2012	3	7	71	59	64	0.00		0.0		0								
	2012	3	8	68	31	33	0.34		0.0		0								
	2012	3	9	51	33	51	0.00		0.0		0								
	2012	3	10	63	32	55	0.00		0.0		0								
	2012	3	11	62	38	46			0.0		0								
	2012	3	12	65	46	56	0.55	A	0.0		0								
	2012	3	13	75	48	52	0.00		0.0		0								
	2012	3	14	81	52	73	0.00		0.0		0								
	2012	3	15	82	61	64	0.00		0.0		0								
	2012	3	16	82	61	63	0.00		0.0		0								
	2012	3	17	82	63	64	0.00		0.0		0								
	2012	3	18	75	64	71	0.00		0.0		0								
	2012	3	19	73	67	68	0.00		0.0		0								
	2012	3	20	69	54	54	1.47		0.0		0								
	2012	3	21	58	54	57	0.37		0.0		0								
	2012	3	22	62	45	49	0.54		0.0		0								
	2012	3	23	64	46	51	0.18		0.0		0								
	2012	3	24	70	51	64	0.00		0.0		0								
	2012	3	25	75	50	57	0.00		0.0		0								
	2012	3	26	79	57	67	0.00		0.0		0								
	2012	3	27	81	64	67	0.00		0.0		0								
	2012	3	28	75	58	69	0.06		0.0		0								
	2012	3	29	80	59	61	0.02		0.0		0								
	2012	3	30	80	60		0.00		0.0		0								
	2012	3	31	81	58	60	0.00		0.0		0								
			Summary	69.8	49.5		3.56		0.0										

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Station: **LAWRENCE, KS US**
Observation Time Temperature: 0700 Observation Time Precipitation: 0700

GHCND:USC00144559
Elev: 1004 ft. Lat: 38.958° N Lon: 95.251° W

Preliminary	Year	Month	Day	Temperature (°F) 24 hrs. ending at observation time Max.	Temperature (°F) 24 hrs. ending at observation time Min.	Temperature (°F) at Observation	Precipitation (see **) 24 Hour Amounts ending at observation time Rain, melted snow, etc. (in)	Flag	Snow, ice pellets, hail (in)	Flag	At Obs Time Snow, ice pellets, hail, ice on ground (in)	Evaporation 24 Hour Wind Movement (mi)	Evaporation Amount of Evap. (in)	Soil Temperature (°F) 4 in depth Ground Cover (see *)	4 in depth Max.	4 in depth Min.	8 in depth Ground Cover (see *)	8 in depth Max.	8 in depth Min.
	2012	4	1	84	60	69	0.00		0.0		0								
	2012	4	2	87	69	75	0.00		0.0		0								
	2012	4	3	87	56	60	0.00												
	2012	4	4	70	58	61	0.12		0.0		0								
	2012	4	5	70	48	48	0.43		0.0		0								
	2012	4	6	64	47	54	0.00		0.0		0								
	2012	4	7	67	42	53	0.00												
	2012	4	8	65	45	50	0.04		0.0		0								
	2012	4	9	67	47	52	0.00		0.0		0								
	2012	4	10	73	43	53	0.00		0.0		0								
	2012	4	11	66	41	45	0.00		0.0		0								
	2012	4	12	64	45	50	0.00		0.0		0								
	2012	4	13	69	49	68	0.17		0.0		0								
	2012	4	14	76	61	63	0.02		0.0		0								
	2012	4	15	75	63	65	0.12		0.0		0								
	2012	4	16	73	51	53	0.00		0.0		0								
	2012	4	17	73	46	61	0.00		0.0		0								
	2012	4	18	74	54	61	0.00		0.0		0								
	2012	4	19	79	58	63	0.00		0.0		0								
	2012	4	20	77	48	48	0.00		0.0		0								
	2012	4	21	64	41	42	0.00		0.0		0								
	2012	4	22	70	42	56	0.00		0.0		0								
	2012	4	23	62	46	56	0.00		0.0		0								
	2012	4	24	68	41	61	0.00												
	2012	4	25	87	61	75	0.00		0.0		0								
	2012	4	26	93	61	77	0.00		0.0		0								
	2012	4	27	81	60	62	T		0.0		0								
	2012	4	28	66	55	57	0.12		0.0		0								
	2012	4	29	68	55				0.0		0								
	2012	4	30	65	55	59	1.52	A	0.0		0								
			Summary	72.8	51.6		2.54		0.0										

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Station: **LAWRENCE, KS US** GHCND:USC00144559
Observation Time Temperature: 0700 Observation Time Precipitation: 0700 Elev: 1004 ft. Lat: 38.958° N Lon: 95.251° W

Preliminary	Year	Month	Day	Temperature (°F) 24 hrs. ending at observation time Max.	Min.	at Observation	Precipitation(see **) 24 Hour Amounts ending at observation time Rain, melted snow, etc. (in)	Flag	Snow, ice pellets, hail (in)	Flag	At Obs Time Snow, ice pellets, hail, ice on ground (in)	Evaporation 24 Hour Wind Movement (mi)	Amount of Evap. (in)	Soil Temperature (°F) 4 in depth Ground Cover (see *)	Max.	Min.	8 in depth Ground Cover (see *)	Max.	Min.
	2012	5	1	68	58	63	0.38		0.0		0								
	2012	5	2	77	63	74	T		0.0		0								
	2012	5	3	82	67	73	0.01		0.0		0								
	2012	5	4	83	70	70	0.06		0.0		0								
	2012	5	5	88	69	70	T		0.0		0								
	2012	5	6	90	70	76	T		0.0		0								
	2012	5	7	82	57	66	1.45		0.0		0								
	2012	5	8	73	51	60	0.00		0.0		0								
	2012	5	9	74	49	51	0.00		0.0		0								
	2012	5	10	73	51	73	0.00		0.0		0								
	2012	5	11	80	58	67	0.00		0.0		0								
	2012	5	12	78	56	59	0.00		0.0		0								
	2012	5	13	67	53		0.00		0.0		0								
	2012	5	14	75	59	68	0.00		0.0		0								
	2012	5	15	79	59	66	0.00		0.0		0								
	2012	5	16	85	51	54	0.00		0.0		0								
	2012	5	17	81	54	72	0.00		0.0		0								
	2012	5	18	87	63		0.00		0.0		0								
	2012	5	19	87	70	73	T		0.0		0								
	2012	5	20	86	67	74	0.00		0.0		0								
	2012	5	21	77	59	61	0.00		0.0		0								
	2012	5	22	76	61	65	0.00		0.0		0								
	2012	5	23	90	65	90	0.00		0.0		0								
	2012	5	24	90	75	75	0.00		0.0		0								
	2012	5	25	87	67	68	0.77		0.0		0								
	2012	5	26	88	68	76	0.02		0.0		0								
	2012	5	27	90	75	88	0.00		0.0		0								
	2012	5	28	90	75	79	0.00		0.0		0								
	2012	5	29	90	63	65	0.00		0.0		0								
	2012	5	30	85	56	65	0.21		0.0		0								
	2012	5	31	81	58	58	0.35		0.0		0								
			Summary	81.9	61.8		3.25		0.0										

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Station: **LAWRENCE, KS US** GHCND:USC00144559
Observation Time Temperature: 0700 Observation Time Precipitation: 0700 Elev: 1004 ft. Lat: 38.958° N Lon: 95.251° W

Preliminary	Year	Month	Day	Temperature (°F) 24 hrs. ending at observation time Max.	Min.	at Observation	Precipitation(see **) 24 Hour Amounts ending at observation time Rain, melted snow, etc. (in)	Flag	Snow, ice pellets, hail (in)	Flag	At Obs Time Snow, ice pellets, hail, ice on ground (in)	Evaporation 24 Hour Wind Movement (mi)	Amount of Evap. (in)	Soil Temperature (°F) 4 in depth Ground Cover (see *)	Max.	Min.	8 in depth Ground Cover (see *)	Max.	Min.
	2012	6	1	66	46	55			0.0		0								
	2012	6	2	65	50	60	0.47	A	0.0		0								
	2012	6	3	83	60	68	0.00		0.0		0								
	2012	6	4	91	61														
	2012	6	5	93	63	63	0.00												
	2012	6	6	86	63	69	0.00		0.0		0								
	2012	6	7	86	67	70	0.00		0.0		0								
	2012	6	8	86	60	63	0.00		0.0		0								
	2012	6	9	95	62														
	2012	6	10	91	73	88	0.00		0.0		0								
	2012	6	11	93	64	67	0.30												
	2012	6	12	87	58	64	0.00												
	2012	6	13	84	59	61	0.00		0.0		0								
	2012	6	14	87	61	83	0.00		0.0		0								
	2012	6	15	94	69	69	T		0.0		0								
	2012	6	16	92	69	78	0.18		0.0		0								
	2012	6	17	90	73	73	0.00		0.0		0								
	2012	6	18	93	73	78	0.00		0.0		0								
	2012	6	19	96	78	84	0.00		0.0		0								
	2012	6	20	91	74	75	0.00		0.0		0								
	2012	6	21	90	65	68	1.40												
	2012	6	22	83	63	67	0.00		0.0		0								
	2012	6	23	86	67	69	0.00		0.0		0								
	2012	6	24	92	68	79	0.00		0.0		0								
	2012	6	25	101	74	78	0.00		0.0		0								
	2012	6	26	97	70	72	0.00		0.0		0								
	2012	6	27	95	72	77	0.00		0.0		0								
	2012	6	28	102	77	77	0.00		0.0		0								
	2012	6	29	104	77	90	0.00		0.0		0								
	2012	6	30	102	82	90	0.00		0.0		0								
			Summary	90.0	66.6		2.35		0.0										

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Station: **LAWRENCE, KS US** GHCND:USC00144559
Observation Time Temperature: 0700 Observation Time Precipitation: 0700 Elev: 1004 ft. Lat: 38.958° N Lon: 95.251° W

Preliminary	Year	Month	Day	Temperature (°F) 24 hrs. ending at observation time Max.	Min.	at Observation	Precipitation (see **) 24 Hour Amounts ending at observation time Rain, melted snow, etc. (in)	Flag	Snow, ice pellets, hail (in)	Flag	At Obs Time Snow, ice pellets, hail, ice on ground (in)	Evaporation 24 Hour Wind Movement (mi)	Amount of Evap. (in)	Soil Temperature (°F) 4 in depth Ground Cover (see *)	Max.	Min.	8 in depth Ground Cover (see *)	Max.	Min.
	2012	7	1	101	80	85	0.00		0.0		0								
	2012	7	2	100	73	73	0.00		0.0		0								
	2012	7	3	97	73	82	0.00		0.0		0								
	2012	7	4	101	82	94	0.00		0.0		0								
	2012	7	5	102	76		0.00		0.0		0								
	2012	7	6	102	75	86	0.00		0.0		0								
	2012	7	7	104	75	88	0.00		0.0		0								
	2012	7	8	104	77	87	Ts		0.0		0								
	2012	7	9	87	74	83	0.16s	A	0.0		0								
	2012	7	10	85	72	75	0.06		0.0		0								
	2012	7	11	92	69	88	0.00		0.0		0								
	2012	7	12	95	70	90	0.00		0.0		0								
	2012	7	13	95	70	73	T		0.0		0								
	2012	7	14	84	70	73	0.16		0.0		0								
	2012	7	15	98	73	92	0.00		0.0		0								
	2012	7	16	99	72	75	0.00												
	2012	7	17	97	75	79	0.00		0.0		0								
	2012	7	18	102	75		0.00		0.0		0								
	2012	7	19	105	70		0.67		0.0		0								
	2012	7	20	105	70	74	0.00		0.0		0								
	2012	7	21	101	69	76	0.00		0.0		0								
	2012	7	22	100	73	78	0.00		0.0		0								
	2012	7	23	103	76	99	0.00		0.0		0								
	2012	7	24	104	75	81	0.00												
	2012	7	25	106	81	101	0.00												
	2012	7	26	104	75	77	0.18		0.0										
	2012	7	27	94	73	80	0.00												
	2012	7	28	94	71	75	0.00												
	2012	7	29	100	74	84	0.00												
	2012	7	30	107	81	86	T		0.0		0								
	2012	7	31	91	78	83	0.02												
			Summary	98.7	74.1		1.25		0.0										

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National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801
www.ncdc.noaa.gov

Station: **LAWRENCE, KS US**
Observation Time Temperature: 0700 Observation Time Precipitation: 0700

GHCND:USC00144559
Elev: 1004 ft. Lat: 38.958° N Lon: 95.251° W

Preliminary	Year	Month	Day	Temperature (°F) 24 hrs. ending at observation time			Precipitation(see **) 24 Hour Amounts ending at observation time				At Obs Time	Evaporation		Soil Temperature (°F) 4 in depth			8 in depth		
				Max.	Min.	at Observation	Rain, melted snow, etc. (in)	Flag	Snow, ice pellets, hail (in)	Flag	Snow, ice pellets, hail, ice on ground (in)	24 Hour Wind Movement (mi)	Amount of Evap. (in)	Ground Cover (see *)	Max.	Min.	Ground Cover (see *)	Max.	Min.
	2012	8	1	100	76	80	0.00												
	2012	8	2	100	73	73	0.21												
	2012	8	3	94	72	78	0.03												
	2012	8	4	94	77	88	0.00												
	2012	8	5	88	65	71	0.00		0.0		0								
	2012	8	6	91	61	79	0.00												
	2012	8	7	97	69	84	0.00												
	2012	8	8	102	73	85	T												
	2012	8	9	85	68	72	0.51												
	2012	8	10	83	66	74	0.00												
	2012	8	11	83	59	70	0.00												
	2012	8	12	89	70	89	T												
	2012	8	13	95	68	70	T												
	2012	8	14	76	60	63	T												
	2012	8	15	74	58	71	0.13												
	2012	8	16	95	71	74	0.00												
	2012	8	17	80	58	77	T												
	2012	8	18	83	58	61	0.00												
	2012	8	19	84	61	83	0.00												
	2012	8	20	84	57	68	0.00												
	2012	8	21	87	65	79	0.00												
	2012	8	22	93	70	81	0.00												
	2012	8	23	96	65	68	0.00												
	2012	8	24	95	68	72	0.00												
	2012	8	25	83	66	67	0.11												
	2012	8	26	82	67	70	0.38												
	2012	8	27	83	67	77	T												
	2012	8	28	91	64	73	0.00												
	2012	8	29	96	64	70	0.00												
	2012	8	30	97	70	81	0.00												
	2012	8	31	99	70	74	0.00												
			Summary	89.6	66.3		1.37		0.0										

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Station: **LAWRENCE, KS US**
Observation Time Temperature: 0700   Observation Time Precipitation: 0700

GHCND:USC00144559
Elev: 1004 ft. Lat: 38.958° N Lon: 95.251° W

Preliminary	Year	Month	Day	Temperature (°F) 24 hrs. ending at observation time			Precipitation(see **) 24 Hour Amounts ending at observation time				At Obs Time	Evaporation		Soil Temperature (°F) 4 in depth			8 in depth		
				Max.	Min.	at Observation	Rain, melted snow, etc. (in)	Flag	Snow, ice pellets, hail (in)	Flag	Snow, ice pellets, hail, ice on ground (in)	24 Hour Wind Movement (mi)	Amount of Evap. (in)	Ground Cover (see *)	Max.	Min.	Ground Cover (see *)	Max.	Min.
	2012	9	1	79	69	71	1.58												
	2012	9	2	87	66	74	0.01												
	2012	9	3	92	71	79	0.00												
	2012	9	4	98	73	80	T												
	2012	9	5	96	73	77	T												
	2012	9	6	94	67	77	0.00												
	2012	9	7	92	74	77	0.00												
	2012	9	8	84	56	65	0.25												
	2012	9	9	80	58	77	0.00												
	2012	9	10	77	66	69	0.00												
	2012	9	11	83	69	72	0.00												
	2012	9	12	91	68	76	0.00												
	2012	9	13	88	54	57	0.00												
	2012	9	14	57	52	55	0.58												
	2012	9	15	69	54	64	0.00												
	2012	9	16	73	61	72	0.00												
	2012	9	17	76	63	66	0.00												
	2012	9	18	78	47	57	T												
	2012	9	19	72	53	56	0.00												
	2012	9	20	84	56	66	0.00												
	2012	9	21	79	55	60	0.00												
	2012	9	22	84	49	54	0.00												
	2012	9	23	70	42	69	0.00												
	2012	9	24	70	50	60	0.00												
	2012	9	25	79	60	67	0.00												
	2012	9	26	80	61	65	0.12												
	2012	9	27	80	59	63	0.02												
	2012	9	28	73	56	59	0.00												
	2012	9	29	73	50	53	0.00												
	2012	9	30	75	53	64	0.00												
			Summary	80.4	59.5		2.56		0										

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Station: **LAWRENCE, KS US** GHCND:USC00144559
Observation Time Temperature: 0700 Observation Time Precipitation: 0700 Elev: 1004 ft. Lat: 38.958° N Lon: 95.251° W

				Temperature (°F)			Precipitation(see **)					Evaporation		Soil Temperature (°F)					
				24 hrs. ending at observation time			24 Hour Amounts ending at observation time				At Obs Time			4 in depth			8 in depth		
Preliminary	Year	Month	Day	Max.	Min.	at Observation	Rain, melted snow, etc. (in)	Flag	Snow, ice pellets, hail (in)	Flag	Snow, ice pellets, hail, ice on ground (in)	24 Hour Wind Movement (mi)	Amount of Evap. (in)	Ground Cover (see *)	Max.	Min.	Ground Cover (see *)	Max.	Min.
	2012	10	1	74	64	66	0.00												
	2012	10	2	80	50	57	0.00												
	2012	10	3	80	50	60	0.00												
	2012	10	4	79	54	56	0.00												
	2012	10	5	58	45	47	0.00												
	2012	10	6	52	39	40	0.00												
	2012	10	7	45	31	37	0.00												
	2012	10	8	57	37	39	0.00												
	2012	10	9	65	39	56	0.00												
	2012	10	10	67	36	41	0.00												
	2012	10	11	65	41	60	0.00												
	2012	10	12	74	54	54	0.00												
	2012	10	13	71	54	66	0.12												
	2012	10	14	68	47	54	1.48												
	2012	10	15	68	54	57	0.00												
	2012	10	16	77	54	67	0.00												
	2012	10	17	82	60	61	0.00												
	2012	10	18	68	48	51	0.06												
	2012	10	19	60	48	49	0.00												
	2012	10	20	55	41	46	0.00												
	2012	10	21	76	46	75	0.00												
	2012	10	22	77	69	76	0.00												
	2012	10	23	81	68	71	T												
	2012	10	24	82	68	71	T												
	2012	10	25	83	33	36	0.02												
	2012	10	26	47	36	38	0.00												
	2012	10	27	47	31	36	0.00												
	2012	10	28	48	30	38	0.00												
	2012	10	29	52	37	45	0.00												
	2012	10	30	58	43	45	0.00												
	2012	10	31	60	36	44	0.00												
			Summary	66.3	46.5		1.68		0										

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Station: **LAWRENCE, KS US** GHCND:USC00144559
Observation Time Temperature: 0700 Observation Time Precipitation: 0700 Elev: 1004 ft. Lat: 38.958° N Lon: 95.251° W

Preliminary	Year	Month	Day	Temperature (°F) 24 hrs. ending at observation time			Precipitation(see **) 24 Hour Amounts ending at observation time				At Obs Time	Evaporation		Soil Temperature (°F) 4 in depth			8 in depth		
				Max.	Min.	at Observation	Rain, melted snow, etc. (in)	Flag	Snow, ice pellets, hail (in)	Flag	Snow, ice pellets, hail, ice on ground (in)	24 Hour Wind Movement (mi)	Amount of Evap. (in)	Ground Cover (see *)	Max.	Min.	Ground Cover (see *)	Max.	Min.
	2012	11	1	61	37	53	0.00												
	2012	11	2	76	42	51	0.00												
	2012	11	3	65	30	40	0.00												
	2012	11	4	63	40	60	0.00												
	2012	11	5	62	44	45	0.00												
	2012	11	6	62	41	48	0.00												
	2012	11	7	60	36	51	0.00												
	2012	11	8	65	39	59	0.00												
	2012	11	9	71	55	71	0.00												
	2012	11	10	74	64	70	T												
	2012	11	11	72	25	36	0.55												
	2012	11	12	43	29	42	0.00												
	2012	11	13	51	29	50	0.00												
	2012	11	14	56	41	53	0.00												
	2012	11	15	58	40	45	0.00												
	2012	11	16	60	45	45	0.00												
	2012	11	17	60	38	40	0.00												
	2012	11	18	63	40	63	0.00												
	2012	11	19	63	48	50	T												
	2012	11	20	66	42	58	0.00												
	2012	11	21	66	42	58	0.00												
	2012	11	22	72	45	62	0.00												
	2012	11	23	70	40	45s	0.00												
	2012	11	24	43s	30	35	0.00												
	2012	11	25	55	35	55	0.00												
	2012	11	26	58	34	38	0.00												
	2012	11	27	42	17	35	0.00												
	2012	11	28	47	17	47	0.00												
	2012	11	29	56	27	55	0.00												
	2012	11	30	61	41	47	0.00												
			Summary	60.7	37.8		0.55		0										

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Station: **LAWRENCE, KS US** GHCND:USC00144559
Observation Time Temperature: 0700 Observation Time Precipitation: 0700 Elev: 1004 ft. Lat: 38.958° N Lon: 95.251° W

Preliminary	Year	Month	Day	Temperature (°F)			Precipitation(see **)					Evaporation		Soil Temperature (°F)					
				24 hrs. ending at observation time		at Observation	24 Hour Amounts ending at observation time				At Obs Time			4 in depth			8 in depth		
				Max.	Min.		Rain, melted snow, etc. (in)	Flag	Snow, ice pellets, hail (in)	Flag	Snow, ice pellets, hail, ice on ground (in)	24 Hour Wind Movement (mi)	Amount of Evap. (in)	Ground Cover (see *)	Max.	Min.	Ground Cover (see *)	Max.	Min.
	2012	12	1	69	47	69	T												
	2012	12	2	69	41	66	0.00												
	2012	12	3	69	56	67	T												
	2012	12	4	71	38	41	0.00												
	2012	12	5	62	41	56	0.00												
	2012	12	6	61	43	48	0.00												
	2012	12	7	52	43	45	0.00												
	2012	12	8	48	32	36	0.00												
	2012	12	9	46	36	43	0.00												
	2012	12	10	43	14	15	0.00												
	2012	12	11	30	15	25	0.00												
	2012	12	12	46	25	39	0.00												
	2012	12	13	50	30	50	0.00												
	2012	12	14	56	35	41	0.00												
	2012	12	15	52	41	43	T												
	2012	12	16	50	32	35	0.00												
	2012	12	17	36	32	35	0.00												
	2012	12	18	45	35	41	0.00												
	2012	12	19	56	36	39	0.00												
	2012	12	20	42	22	23	0.33		2.4		2								
	2012	12	21	28	18	22	0.00		0.0		2								
	2012	12	22	38	22	30	0.00		0.0		1								
	2012	12	23	51	30	37	0.00		0.0		T								
	2012	12	24	37	16	20	0.00		0.0		T								
	2012	12	25	24	16	16	0.00		0.0		0								
	2012	12	26	21	8	8	0.00		0.0		0								
	2012	12	27	26	8	20	0.00		0.0		0								
	2012	12	28	38	19	27	0.00		0.0		0								
	2012	12	29	28	17	17	0.00		0.0		0								
	2012	12	30	36	17	25	0.00		0.0		0								
	2012	12	31	45	25	33	0.00		0.0		0								
			Summary	46.0	28.7		0.33		2.4										

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Station: **LAWRENCE, KS US**
Observation Time Temperature: 0700 Observation Time Precipitation: 0700

GHCND:USC00144559
Elev: 1004 ft. Lat: 38.958° N Lon: 95.251° W

Preliminary	Year	Month	Day	Temperature (°F) 24 hrs. ending at observation time Max.	Min.	at Observation	Precipitation(see **) 24 Hour Amounts ending at observation time Rain, melted snow, etc. (in)	Flag	Snow, ice pellets, hail (in)	Flag	At Obs Time Snow, ice pellets, hail, ice on ground (in)	Evaporation 24 Hour Wind Movement (mi)	Amount of Evap. (in)	Soil Temperature (°F) 4 in depth Ground Cover (see *)	Max.	Min.	8 in depth Ground Cover (see *)	Max.	Min.
	2013	1	1	33	12	14	0.19		1.7		2								
	2013	1	2	24	10	14	0.00		0.0		2								
	2013	1	3	28	14	28	0.00		0.0		1								
	2013	1	4	37	18	31	0.00		0.0		T								
	2013	1	5	38	28	30	0.00												
	2013	1	6	47	22	38	0.00												
	2013	1	7	41	32	40	0.00												
	2013	1	8	50	40	47	0.00												
	2013	1	9	54	29	48	0.00		0.0		0								
	2013	1	10	51	32	38	0.12		0.0		0								
	2013	1	11	50	38	50	0.48												
	2013	1	12	50	30	35	0.00												
	2013	1	13	35	18	20	T		T		0								
	2013	1	14	32	10	32	0.00												
	2013	1	15	33	16	30	0.00												
	2013	1	16	39	18	39	0.00												
	2013	1	17	49	30	42	0.00												
	2013	1	18	49	35	44	0.00												
	2013	1	19	60	38	40	0.00												
	2013	1	20	62	25	32	0.00												
	2013	1	21	35	18	21	0.00												
	2013	1	22	27	12	27	0.00												
	2013	1	23	36	16	29	0.00												
	2013	1	24	48	10	25	0.00												
	2013	1	25	31	20	31	0.00												
	2013	1	26	48	31	38	0.00												
	2013	1	27	57	38	45	0.04												
	2013	1	28	70	43	70	0.00												
	2013	1	29	74	37	38	0.22												
	2013	1	30	38	24	26	0.10		1.0		1								
	2013	1	31	27	19	20	T		T		T								
			Summary	43.6	24.6		1.15		2.7										

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Station: **LAWRENCE, KS US** GHCND:USC00144559
Observation Time Temperature: 0700 Observation Time Precipitation: 0700 Elev: 1004 ft. Lat: 38.958° N Lon: 95.251° W

Preliminary	Year	Month	Day	Temperature (°F)			Precipitation(see **)					Evaporation		Soil Temperature (°F)					
				24 hrs. ending at observation time		at Observation	24 Hour Amounts ending at observation time				At Obs Time			4 in depth			8 in depth		
				Max.	Min.		Rain, melted snow, etc. (in)	Flag	Snow, ice pellets, hail (in)	Flag	Snow, ice pellets, hail, ice on ground (in)	24 Hour Wind Movement (mi)	Amount of Evap. (in)	Ground Cover (see *)	Max.	Min.	Ground Cover (see *)	Max.	Min.
	2013	2	1	26	8	24	0.00		0.0		T								
	2013	2	2	43	24	43	0.00												
	2013	2	3	50	33	38	0.00												
	2013	2	4	49	38	39	0.00												
	2013	2	5	50	23	50	0.00												
	2013	2	6	59	24	51	0.00												
	2013	2	7	62	41	45	0.89												
	2013	2	8	51	31	38	T												
	2013	2	9	45	32	37	0.00												
	2013	2	10	50	37	44													
	2013	2	11	46	30	45	0.00												
	2013	2	12	45	27	38	0.00												
	2013	2	13	45	27	41	0.00												
	2013	2	14	56	38	41	0.00												
	2013	2	15	52	30	33	0.00												
	2013	2	16	40	29	33	0.33		2.6		2								
	2013	2	17	33	24	33	0.00		0.0		0								
	2013	2	18	54	33	42	T												
	2013	2	19	44	22	27	0.00												
	2013	2	20	36	15	23	0.00												
	2013	2	21	28	18	24	1.42		7.6		8								
	2013	2	22	27	18	22	0.05		2.2		10								
	2013	2	23	31	18	31	0.00		0.0		10								
	2013	2	24	44	18	44	0.00		0.0		8								
	2013	2	25	46	30	33	0.00		0.0		5								
	2013	2	26	37	32	35	0.82		7.6		10								
	2013	2	27	35	27	29	T		T		9								
	2013	2	28	38	28	30	0.00		0.0		6								
			Summary	43.6	27.0		3.51		20.0										

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Station: **LAWRENCE, KS US** GHCND:USC00144559
Observation Time Temperature: 0700 Observation Time Precipitation: 0700 Elev: 1004 ft. Lat: 38.958° N Lon: 95.251° W

Preliminary	Year	Month	Day	Temperature (°F)			Precipitation(see **)					Evaporation		Soil Temperature (°F)					
				24 hrs. ending at observation time		at Observation	24 Hour Amounts ending at observation time				At Obs Time			4 in depth			8 in depth		
				Max.	Min.		Rain, melted snow, etc. (in)	Flag	Snow, ice pellets, hail (in)	Flag	Snow, ice pellets, hail, ice on ground (in)	24 Hour Wind Movement (mi)	Amount of Evap. (in)	Ground Cover (see *)	Max.	Min.	Ground Cover (see *)	Max.	Min.
	2013	3	1	33	25	25	T		T		4								
	2013	3	2	32	20	31	0.00		0.0		4								
	2013	3	3	44	31	44	0.00		0.0		3								
	2013	3	4	49	21	40	0.00		0.0		1								
	2013	3	5	48	21	33	0.00		0.0		T								
	2013	3	6	40	33	35	0.00		0.0		T								
	2013	3	7	36	28	30	0.00		0.0		T								
	2013	3	8	55	30	55	0.00		0.0		T								
	2013	3	9	55	35	37			0.0		0								
	2013	3	10	57	37	37	0.92	A	0.0		0								
	2013	3	11	37	23	25	T		T		0								
	2013	3	12	43	25	42	0.00		0.0		0								
	2013	3	13	47	24	29	0.00		0.0		0								
	2013	3	14	47	24	42	0.00		0.0		0								
	2013	3	15	75	42	75	0.00		0.0		0								
	2013	3	16	83	39	39	0.00		0.0		0								
	2013	3	17	46	31	31	T		0.0		0								
	2013	3	18	36	31	35	0.15		0.0		0								
	2013	3	19	54	30	32	0.00		0.0		0								
	2013	3	20	38	22	23	0.18		0.0		0								
	2013	3	21	40	23	27	0.00		0.0		0								
	2013	3	22	30	26	28	0.08		0.0		0								
	2013	3	23	32	28	32	0.01		0.0		0								
	2013	3	24	37	26	26	0.56		4.2		4								
	2013	3	25	32	20	28	T		T		4								
	2013	3	26	31	22	31	T		T		4								
	2013	3	27	43	26	43	0.00		0.0		1								
	2013	3	28	45	34	40	0.00		0.0		T								
	2013	3	29	70	40	70	0.00		0.0		0								
	2013	3	30	70	41	44	0.00		0.0		0								
	2013	3	31	69	44	50	0.05		0.0		0								
			Summary	46.9	29.1		1.95		4.2										

U.S. Department of Commerce
National Oceanic & Atmospheric Administration
National Environmental Satellite, Data, and Information Service

Record of Climatological Observations

These data are quality controlled and may not be identical to the original observations.

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801
www.ncdc.noaa.gov

Station: **LAWRENCE, KS US** GHCND:USC00144559
Observation Time Temperature: 0700 Observation Time Precipitation: 0700 Elev: 1004 ft. Lat: 38.958° N Lon: 95.251° W

Preliminary	Year	Month	Day	Temperature (°F) 24 hrs. ending at observation time Max.	Min.	at Observation	Precipitation(see **) 24 Hour Amounts ending at observation time Rain, melted snow, etc. (in)	Flag	Snow, ice pellets, hail (in)	Flag	At Obs Time Snow, ice pellets, hail, ice on ground (in)	Evaporation 24 Hour Wind Movement (mi)	Amount of Evap. (in)	Soil Temperature (°F) 4 in depth Ground Cover (see *)	Max.	Min.	8 in depth Ground Cover (see *)	Max.	Min.
	2013	4	1	64	32	41	0.00		0.0		0								
	2013	4	2	46	27	41	0.00		0.0		0								
	2013	4	3	51	31	48	0.00		0.0		0								
	2013	4	4	53	37	53	0.00		0.0		0								
	2013	4	5	63	34	63	0.00		0.0		0								
	2013	4	6	73	38	73	0.00		0.0		0								
	2013	4	7	76	52	55	0.00		0.0		0								
	2013	4	8	70	55	68	0.55		0.0		0								
	2013	4	9	71	64	66	T		0.0		0								
	2013	4	10	74	37	70			0.0		0								
	2013	4	11	70	32	38	1.20	A	T		0								
	2013	4	12	55	33	40	0.00		0.0		0								
	2013	4	13	67	34	40	0.00		0.0		0								
	2013	4	14	72	40	50	0.00		0.0		0								
	2013	4	15	69	43	47	0.16		0.0		0								
	2013	4	16	49	39	44	0.00		0.0		0								
	2013	4	17	50	44	47	0.02		0.0		0								
	2013	4	18	49	35	36	0.59		0.0		0								
	2013	4	19	52	31	50	0.00												
	2013	4	20	53	31	50	0.00												
	2013	4	21	60	31	59	0.00												
	2013	4	22	65	31	56	0.00												
	2013	4	23	61	31	32	0.31		T		0								
	2013	4	24	37	28	35	0.03		T		0								
	2013	4	25	56	35	46	0.00		0.0		0								
	2013	4	26	70	36	52	0.62		0.0		0								
	2013	4	27	69	47	53	0.53		0.0		0								
	2013	4	28	73	44	72	0.00		0.0		0								
	2013	4	29	74	45	69	0.00		0.0		0								
	2013	4	30	83	66	81	0.00		0.0		0								
			Summary	62.5	38.8		4.01		0.0										

U.S. Department of Commerce
National Oceanic & Atmospheric Administration
National Environmental Satellite, Data, and Information Service

Record of Climatological Observations

These data are quality controlled and may not be identical to the original observations.

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801
www.ncdc.noaa.gov

Station: **LAWRENCE, KS US** GHCND:USC00144559
Observation Time Temperature: 0700 Observation Time Precipitation: 0700 Elev: 1004 ft. Lat: 38.958° N Lon: 95.251° W

Preliminary	Year	Month	Day	Temperature (°F)			Precipitation(see **)					Evaporation		Soil Temperature (°F)					
				24 hrs. ending at observation time		at Observation	24 Hour Amounts ending at observation time				At Obs Time			4 in depth			8 in depth		
				Max.	Min.		Rain, melted snow, etc. (in)	Flag	Snow, ice pellets, hail (in)	Flag	Snow, ice pellets, hail, ice on ground (in)	24 Hour Wind Movement (mi)	Amount of Evap. (in)	Ground Cover (see *)	Max.	Min.	Ground Cover (see *)	Max.	Min.
	2013	5	1	83	61	68	0.00		0.0		0								
	2013	5	2	78	34	34	0.11		0.0		0								
	2013	5	3	60	33	40			T		0								
	2013	5	4	46	33	44	1.16	A	0.0		0								
	2013	5	5	53	43	53	T		0.0		0								
	2013	5	6	66	44	53	0.00		0.0		0								
	2013	5	7	69	47	68	0.00		0.0		0								
	2013	5	8	74	57	66	0.06		0.0		0								
	2013	5	9	74	58	68	0.71		0.0		0								
	2013	5	10	73	52	58	0.02		0.0		0								
	2013	5	11	69	48	67	0.00		0.0		0								
	2013	5	12	68	42	49	0.00		0.0		0								
	2013	5	13	78	49	64	0.00		0.0		0								
	2013	5	14	87	64	87	0.00		0.0		0								
	2013	5	15	93	66	85	0.00		0.0		0								
	2013	5	16	87	62	68	0.00												
	2013	5	17	81	61	62	0.03												
	2013	5	18	79	62	64	0.00												
	2013	5	19	83	61		0.00												
	2013	5	20	82	60	62	0.62												
	2013	5	21	80	57	59	0.00												
	2013	5	22	75	54	54	0.00												
	2013	5	23	68	52	57	0.00												
	2013	5	24	68	51	58	0.00												
	2013	5	25	74	51	63	0.00												
	2013	5	26	82	63	71	0.00												
	2013	5	27	81	61	72	0.00												
	2013	5	28	82	68	72	2.02												
	2013	5	29	80	66	75	T												
	2013	5	30	79	62	62	0.20												
	2013	5	31	74	59	63	2.02												
			Summary	75.0	54.2		6.95		0.0										

Appendix E: Power Plant Steam Production and Makeup Water Tables [Reproduced from Ref. 26]

Makeup Water	%	Feb 2012	#7	#8	#1	#2	HRS. on OIL	OIL Gals.	GAS FEET M.	No. 7 Steam Lbs.	No. 8 Steam Lbs.	No. 1 Steam Lbs.	No. 2 Steam Lbs.	By GAS STEAM LBS.	By OIL STEAM LBS.	TOTAL STEAM GENERATED	BOILER EFF.
21,970	20.1	1	x			x			953,500	893,200			14,200	907,400		907,400	83
19,980	19.2	2	x						921,200	863,700				863,700		863,700	83
18,560	16.3	3	x		x				1,011,100	791,800		153,500		945,300		945,300	82
19,620	15.3	4	x		x				1,130,700	535,100		527,900		1,063,000		1,063,000	81
20,490	15.4	5	x		x				1,164,300	565,700		535,100		1,100,800		1,100,800	81
21,990	16.4	6	x		x	x			1,178,700	577,800		533,600	0	1,111,400		1,111,400	83
23,940	17.2	7	x		x				1,224,600	582,900		574,200		1,157,100		1,157,100	81
24,610	16.4	8	x		x				1,318,400	616,800		625,400		1,242,200		1,242,200	82
25,650	17.6	9	x		x				1,289,900	602,000		609,500		1,211,500		1,211,500	82
28,350	17.1	10	x		x				1,475,500	679,700		698,800		1,378,500		1,378,500	81
33,560	17.6	11	x		x				1,704,100	794,800		792,300		1,587,100		1,587,100	83
29,080	16.3	12	x		x				1,590,800	747,600		732,900		1,480,500		1,480,500	81
28,010	16.8	13	x		x				1,492,600	695,900		687,900		1,383,800		1,383,800	81
24,230	16.8	14	x		x				1,291,200	612,800		587,800		1,200,600		1,200,600	82
20,460	15.8	15	x		x				1,146,100	559,800		515,500		1,075,300		1,075,300	82
22,380	17.1	16	x		x				1,159,800	564,800		523,800		1,088,600		1,088,600	81
19,540	16.4	17	x		x				1,047,500	755,400		231,800		987,200		987,200	82
21,640	19.5	18	x			x			1,160,000	656,200			264,300	920,500		920,500	81
22,310	17.4	19	x			x			1,136,100	535,800			527,600	1,063,400		1,063,400	80
23,120	18.1	20	x			x			114,300	536,200			525,300	1,061,500		1,061,500	81
24,380	19.0	21	x			x			1,131,800	744,000			322,400	1,066,400		1,066,400	83
21,720	19.9	22	x						973,800	905,200				905,200		905,200	83
23,490	21.4	23	x			x			960,800	774,400			136,000	910,400		910,400	83
30,540	23.4	24	x			x			1,169,700	513,500			569,300	1,082,800		1,082,800	81
31,540	23.6	25	x			x			1,186,200	553,400			555,200	1,108,600		1,108,600	81
27,770	25.8	26	x			x			951,000	647,100			245,200	892,300		892,300	79
31,020	23.9	27	x			x			1,163,800	669,500			407,900	1,077,400		1,077,400	80
22,330	20.7	28	x						957,000	674,900			221,600	896,500		896,500	82
22,640	19.8	29	x	x					1,084,000	418,800	532,600			951,400		951,400	83
	######	30												0		0	
	######	31												0		0	
704,920	18.4									19,068,800	532,600	8,330,000	3,789,000	31,720,400	0	31,720,400	

Average Of Steam Produced (lbs)
Monthly average
1,093,807

Average While Grundfos CRE 15-3 was in Operation (lbs)
1,257,586

Average While Worthington D-824 was in Operation (lbs)
999,675

Makeup Water	%	Mar 2012	#7	#8	#1	#2	HRS. on OIL	OIL Gals.	GAS FEET M.	No. 7 Steam Lbs.	No. 8 Steam Lbs.	No. 1 Steam Lbs.	No. 2 Steam Lbs.	By GAS STEAM LBS.	By OIL STEAM LBS.	TOTAL STEAM GENERATED	BOILER EFF.
21,190	23.8	1		x					1,006,500		740,500			740,500		740,500	80
20,620	16.9	2	x	x	x				1,178,000	43,700	868,300	98,800		1,010,800		1,010,800	80
21,070	16.3	3		x	x				1,256,800		889,400	183,900		1,073,300		1,073,300	80
20,900	17.4	4		x	x				1,164,700		766,700	233,000		999,700		999,700	80
21,190	18.3	5		x	x				996,200		759,000	204,500		963,500		963,500	75
13,380	16.2	6		x					806,000		684,400			684,400		684,400	83
13,420	15.7	7		x					827,600		707,800			707,800		707,800	83
27,420	33.3	8		x	x				1,016,300		684,400			684,400		684,400	80
22,640	26.5	9		x	x				967,700		707,800			707,800		707,800	80
17,030	14.2	10		x					938,600		792,000	200,600		992,600		992,600	83
14,880	13.1	11		x					821,600		737,700	202,200		939,900		939,900	82
14,150	14.2	12		x	x				844,300		827,300			827,300		827,300	81
9,550	9.8	13		x					749,600		809,200			809,200		809,200	83
8,390	9.7	14		x		x			661,300		684,000	31,000		715,000		715,000	81
7,970	10.3	15				x			641,800		642,800			642,800		642,800	81
8,270	11.8	16				x			544,600		216,500		366,400	582,900		582,900	81
7,950	11.4	17				x			644,800				578,600	578,600		578,600	81
7,840	11.1	18				x			643,900				583,700	583,700		583,700	81
7,960	10.5	19				x			696,100				628,200	628,200		628,200	81
9,960	11.8	20				x			776,200				699,200	699,200		699,200	81
8,890	10.5	21				x			787,700				704,000	704,000		704,000	82
10,210	10.7	22				x			893,400				795,300	795,300		795,300	81
9,540	10.5	23				x			837,700				751,400	751,400		751,400	82
8,710	11.0	24				x			729,400				655,300	655,300		655,300	81
8,090	11.2	25				x			670,300				600,600	600,600		600,600	82
10,490	16.4	26				x			661,100				529,900	529,900		529,900	82
10,640	15.1	27				x			653,700				585,700	585,700		585,700	81
8,400	12.1	28				x			641,300				575,400	575,400		575,400	82
9,450	13.7	29				x			642,800				573,300	573,300		573,300	81
9,180	13.4	30				x			630,400				566,700	566,700		566,700	82
8,550	13.0	31				x			607,000				545,200	545,200		545,200	82
397,930	**14.7**									**43,700**	**11,517,800**	**1,154,000**	**9,738,900**	**22,454,400**	**0**	**22,454,400**	

Average Of Steam Produced (lbs)
Monthly average
724,335

Average While Grundfos CRE 15-3 was in Operation (lbs)
882,857

Average While Worthington D-824 was in Operation (lbs)
798,000

Makeup Water	%	apr 2012	#7	#8	#1	#2	HRS. on OIL	OIL Gals.	GAS FEET M.	No. 7 Steam Lbs.	No. 8 Steam Lbs.	No. 1 Steam Lbs.	No. 2 Steam Lbs.	By GAS STEAM LBS.	By OIL STEAM LBS.	TOTAL STEAM GENERATED	BOILER EFF.
6,510	10.0	1				x			598,900				537,800	537,800		537,800	81
8,550	14.5	2			x	x			542,200			267,500	222,800	490,300		490,300	75
6,690	9.6	3			x				640,200			578,800		578,800		578,800	82
11,010	14.6	4			x				693,700			624,700		624,700		624,700	82
9,670	11.9	5	x						750,500	302,100		371,200		673,300		673,300	79
10,330	12.9	6	x						711,400	662,400				662,400		662,400	82
9,550	12.7	7	x						664,900	623,800				623,800		623,800	83
11,510	14.7	8	x						690,400	650,900				650,900		650,900	83
13,160	17.3	9	x						670,500	630,300				630,300		630,300	83
11,990	14.0	10	x	x					785,900	322,000	387,200			709,200		709,200	83
15,370	16.6	11		x					891,000		766,600			766,600		766,600	83
14,550	15.5	12		x					920,700		779,900			779,900		779,900	83
10,420	13.6	13		x					752,900		635,900			635,900		635,900	83
8,460	12.4	14		x					667,000		565,700			565,700		565,700	83
9,080	13.2	15		x					668,500		569,300			569,300		569,300	83
11,920	14.8	16		x					789,000		666,900			666,900		666,900	83
12,350	15.6	17	x	x				6188	773,700	58,600	597,900			656,500		656,500	82
7,750	11.2	18		x					677,300		574,800			574,800		574,800	83
6,940	10.1	19		x					670,200		570,100			570,100		570,100	82
11,240	12.7	20		x					861,100		733,500			733,500		733,500	83
9,060	12.0	21		x					811,500		628,400			628,400		628,400	83
9,450	11.3	22		x					816,500		692,000			692,000		692,000	82
9,780	11.4	23		x	x				815,800		358,100	354,800		712,900		712,900	82
8,210	11.5	24			x				657,400			590,900		590,900		590,900	81
7,200	11.3	25			x				585,400			527,600		527,600		527,600	81
7,460	11.9	26			x				574,800			521,600		521,600		521,600	81
6,880	9.8	27			x				648,000			584,900		584,900		584,900	82
7,980	11.0	28			x				665,800			601,200		601,200		601,200	82
6,920	8.8	29			x				731,200			653,800		653,800		653,800	82
12,780	21.1	30		x	x				557,400		213,000	288,700		501,700		501,700	82
	######	31												0		0	
292,770	**13.0**									**3,250,100**	**8,739,300**	**5,965,700**	**760,600**	**18,715,700**	**0**	**18,715,700**	

Average Of Steam Produced (lbs)
Monthly average
623,857

Average While Grundfos CRE 15-3 was in Operation (lbs)
668,750

Average While Worthington D-824 was in Operation (lbs)
652,600

Makeup Water	%	may 2012	#7	#8	#1	#2	HRS. on OIL	OIL Gals.	GAS FEET M.	No. 7 Steam Lbs.	No. 8 Steam Lbs.	No. 1 Steam Lbs.	No. 2 Steam Lbs.	By GAS STEAM LBS.	By OIL STEAM LBS.	TOTAL STEAM GENERATED	BOILER EFF.
12,400	15.7	1			x				777,200			655,300		655,300		655,300	81
8,150	12.2	2			x				613,100			555,200		555,200		555,200	81
7,970	12.2	3			x				601,200			541,200		541,200		541,200	81
8,750	13.9	4			x				576,700			523,000		523,000		523,000	81
5,750	9.4	5			x				559,900			506,400		506,400		506,400	81
11,030	17.7	6			x				573,400			518,600		518,600		518,600	81
11,910	17.8	7			x				613,900			555,100		555,100		555,100	81
10,300	15.2	8			x				619,800			564,100		564,100		564,100	81
8,760	12.1	9			x	x			651,700			335,600	263,600	599,200		599,200	81
8,450	12.7	10				x			610,400				553,600	553,600		553,600	781
8,530	13.5	11				x			576,800				524,300	524,300		524,300	81
8,160	12.3	12				x			602,400				550,200	550,200		550,200	81
6,220	12.8	13				x			471,800				404,300	404,300		404,300	78
	######	14												0		0	
	######	15												0		0	
	######	16												0		0	
	######	17												0		0	
16,830	33.1	18	x			x			578,800	293,400			129,100	422,500		422,500	73
11,530	20.6	19	x						504,700	463,700				463,700		463,700	82
10,670	19.7	20	x						486,900	450,300				450,300		450,300	82
11,830	19.5	21	x						540,700	503,100				503,100		503,100	82
11,540	19.6	22	x						520,700	487,800				487,800		487,800	82
9,510	17.3	23	x						498,500	457,400				457,400		457,400	82
9,190	17.3	24	x						469,300	440,100				440,100		440,100	82
9,150	17.4	25	x						452,200	436,400				436,400		436,400	82
8,930	12.9	26	x						596,600	576,700				576,700		576,700	82
9,020	16.6	27	x						473,100	452,100				452,100		452,100	82
8,820	16.9	28	x						461,700	434,200				434,200		434,200	82
9,100	17.0	29	x	x					508,100	163,200	280,100			443,300		443,300	82
8,130	14.0	30		x					554,300		482,500			482,500		482,500	83
9,060	14.5	31		x					583,700		519,600			519,600		519,600	83
259,690	15.8									5,158,400	1,282,200	4,754,500	2,425,100	13,620,200	0	13,620,200	

Average Of Steam Produced (lbs)
Monthly average
504,452

Average While Grundfos CRE 15-3 was in Operation (lbs)
579,625

Average While Worthington D-824 was in Operation (lbs)
552,363

Makeup Water	%	jun 2012	#7	#8	#1	#2	HRS. on OIL	OIL Gals.	GAS FEET M.	No. 7 Steam Lbs.	No. 8 Steam Lbs.	No. 1 Steam Lbs.	No. 2 Steam Lbs.	By GAS STEAM LBS.	By OIL STEAM LBS.	TOTAL STEAM GENERATED	BOILER EFF.
9,480	14.4	1		x					583,400		546,300			546,300		546,300	83
8,360	13.8	2		x					542,100		503,500			503,500		503,500	83
8,010	13.6	3		x					517,700		489,500			489,500		489,500	83
8,350	14.2	4		x					513,200		487,000			487,000		487,000	82
8,170	14.2	5		x					574,300		479,100			479,100		479,100	82
7,970	13.6	6		x	x				563,800		253,600	233,900		487,500		487,500	81
7,890	13.4	7			x				536,700			487,000		487,000		487,000	80
7,980	13.6	8			x				539,700			485,900		485,900		485,900	81
7,800	13.9	9			x				513,700			465,300		465,300		465,300	80
7,760	14.0	10			x				510,200			460,100		460,100		460,100	81
9,000	15.0	11			x				553,500			497,000		497,000		497,000	81
8,560	14.4	12			x				550,400			492,700		492,700		492,700	81
9,300	15.8	13			x				546,100			488,200		488,200		488,200	81
9,770	17.2	14			x				529,300			470,600		470,600		470,600	81
9,010	15.6	15			x				535,600			478,200		478,200		478,200	80
8,380	15.2	16			x				509,300			458,300		458,300		458,300	81
9,710	18.0	17			x				497,000			448,300		448,300		448,300	81
8,000	15.1	18			x	x			500,900			205,400	235,200	440,600		440,600	80
8,330	15.3	19				x			504,200				452,300	452,300		452,300	81
8,900	16.3	20				x			509,500				453,200	453,200		453,200	80
8,790	15.5	21				x			525,700				469,800	469,800		469,800	80
9,150	16.2	22				x			524,300				470,000	470,000		470,000	80
8,260	15.3	23				x			500,500				448,700	448,700		448,700	80
7,740	15.3	24				x			470,100				420,300	420,300		420,300	80
8,160	15.5	25				x			489,200				437,700	437,700		437,700	80
8,560	15.5	26				x			512,700				459,800	459,800		459,800	80
8,140	15.2	27				x			498,600				444,000	444,000		444,000	80
8,320	15.9	28				x			488,200				435,600	435,600		435,600	80
7,820	14.7	29				x			487,800				440,200	440,200		440,200	80
8,650	16.9	30				x			472,600				424,000	424,000		424,000	80
	#DIV/0!	31												0		0	
254,320	15.1									0	2,759,000	5,670,900	5,590,800	14,020,700	0	14,020,700	

Makeup Water	%	jul 2012	#7	#8	#1	#2	HRS. on OIL	OIL Gals.	GAS FEET M.	No. 7 Steam Lbs.	No. 8 Steam Lbs.	No. 1 Steam Lbs.	No. 2 Steam Lbs.	By GAS STEAM LBS.	By OIL STEAM LBS.	TOTAL STEAM GENERATED	BOILER EFF.
6,280	12.1	1				x			481,100				431,200	431,200		431,200	81
8,270	15.0	2	x			x			479,300	183,800			273,500	457,300		457,300	81
8,020	16.2	3	x						455,700	409,900				409,900		409,900	81
8,370	17.0	4	x						455,300	407,600				407,600		407,600	81
7,860	16.2	5	x						448,400	402,800				402,800		402,800	81
7,850	16.2	6	x						447,500	401,800				401,800		401,800	81
7,520	16.0	7	x						433,800	389,400				389,400		389,400	81
7,690	15.4	8	x						457,400	414,400				414,400		414,400	81
8,320	15.8	9	x						486,100	437,200				437,200		437,200	81
9,940	19.0	10	x						480,600	433,700				433,700		433,700	81
8,660	16.3	11	x						486,400	441,100				441,100		441,100	81
8,810	16.6	12	x						483,300	440,300				440,300		440,300	81
8,840	15.9	13	x						504,800	462,900				462,900		462,900	81
8,160	15.5	14	x						480,900	436,300				436,300		436,300	81
8,060	15.7	15	x						470,400	424,900				424,900		424,900	81
8,560	16.0	16	x						491,600	445,100				445,100		445,100	81
8,780	16.8	17	x						482,300	434,000				434,000		434,000	81
8,730	17.2	18	x						468,200	421,600				421,600		421,600	81
9,520	18.7	19	x						499,800	423,000				423,000		423,000	81
8,820	17.1	20	x						475,600	428,700				428,700		428,700	81
8,840	17.8	21	x						456,700	411,100				411,100		411,100	81
8,390	17.4	22	x						443,600	401,200				401,200		401,200	81
9,730	19.8	23	x						452,800	408,400				408,400		408,400	81
7,840	16.0	24	x						458,600	405,500				405,500		405,500	81
8,300	16.7	25	x						459,700	412,600				412,600		412,600	82
9,900	18.8	26	x						483,700	438,100				438,100		438,100	82
7,770	15.2	27	x						470,100	424,600				424,600		424,600	81
7,350	15.7	28	x						429,100	387,401				387,401		387,401	81
7,310	16.3	29	x						415,600	372,200				372,200		372,200	81
7,470	20.4	30	x		x				346,300	149,500		154,600		304,100		304,100	81
7,360	13.7	31			x				477,100			445,700		445,700		445,700	80
257,320	16.5									11,649,101	0	600,300	704,700	12,954,101	0	12,954,101	

Makeup Water	%	aug 2012	#7	#8	#1	#2	HRS. on OIL	OIL Gals.	GAS FEET M.	No. 7 Steam Lbs.	No. 8 Steam Lbs.	No. 1 Steam Lbs.	No. 2 Steam Lbs.	By GAS STEAM LBS.	By OIL STEAM LBS.	TOTAL STEAM GENERATED	BOILER EFF.
13,480	27.1	1			x				326,200			413,000		413,000		413,000	80
12,860	23.4	2			x				508,700			456,400		456,400		456,400	81
17,400	32.1	3			x				503,800			450,500		450,500		450,500	81
19,250	36.0	4			x				498,300			443,500		443,500		443,500	81
18,540	34.3	5			x				503,900			449,200		449,200		449,200	80
17,170	31.5	6			x				509,000			453,000		453,000		453,000	81
15,350	29.1	7			x				493,100			438,300		438,300		438,300	82
12,350	23.3	8			x				501,300			439,500		439,500		439,500	81
11,260	19.8	9			x				530,000			472,200		472,200		472,200	81
8,850	15.3	10			x				534,300			478,700		478,700		478,700	81
8,640	15.8	11			x				497,500			452,500		452,500		452,500	82
8,910	16.7	12			x				497,600			443,300		443,300		443,300	81
10,370	18.5	13	x		x				522,100	200,000		266,100		466,100		466,100	82
13,650	22.8	14	x						538,400	497,400				497,400		497,400	82
11,940	21.3	15	x						513,200	466,000				466,000		466,000	82
10,680	15.0	16	x	x					632,200	294,900	296,400			591,300		591,300	81
9,670	15.5	17		x					579,100		517,300			517,300		517,300	82
10,140	16.7	18		x					544,200		505,100			505,100		505,100	81
9,670	16.0	19		x					541,500		501,000			501,000		501,000	81
8,650	13.5	20		x		x			560,600		217,700		314,500	532,200		532,200	81
8,450	14.8	21				x			530,100				473,100	473,100		473,100	81
9,230	16.6	22				x			525,400				461,400	461,400		461,400	81
9,920	17.0	23				x			521,700				484,400	484,400		484,400	82
9,300	15.7	24				x			533,100				492,300	492,300		492,300	81
8,640	14.4	25				x			536,100				497,000	497,000		497,000	80
8,990	14.1	26		x		x			557,100		356,200		172,300	528,500		528,500	82
8,600	13.6	27		x		x			557,000		296,500		229,500	526,000		526,000	81
9,090	17.7	28		x		x			486,100		5,900		419,500	425,400		425,400	80
9,190	16.4	29			x	x			529,200		1,000		465,300	466,300		466,300	80
9,050	16.4	30				x			509,600				458,700	458,700		458,700	80
9,150	15.1	31				x			561,600				503,400	503,400		503,400	80
348,440	**19.6**									**1,458,300**	**2,697,100**	**5,656,200**	**4,971,400**	**14,783,000**	**0**	**14,783,000**	

Makeup Water	%	sep 2012	#7	#8	#1	#2	HRS. on OIL	OIL Gals.	GAS FEET M.	No. 7 Steam Lbs.	No. 8 Steam Lbs.	No. 1 Steam Lbs.	No. 2 Steam Lbs.	By GAS STEAM LBS.	By OIL STEAM LBS.	TOTAL STEAM GENERATED	BOILER EFF.
8,760	14.9	1				x			543,800				486,800	486,800		486,800	80
8,140	14.2	2				x			530,000				476,200	476,200		476,200	80
7,570	14.6	3	x			x			481,500	270,400			160,700	431,100		431,100	77
13,610	26.0	4	x						480,900	435,100				435,100		435,100	81
13,050	24.8	5	x						483,500	437,000				437,000		437,000	81
10,090	19.0	6	x						484,200	440,200				440,200		440,200	82
8,530	14.9	7	x						522,400	476,600				476,600		476,600	82
9,050	15.8	8	x						518,700	475,400				475,400		475,400	82
8,870	15.7	9	x						511,100	468,400				468,400		468,400	82
9,770	16.3	10	x						539,500	496,900				496,900		496,900	82
9,640	17.0	11	x						517,000	471,800				471,800		471,800	82
9,990	18.2	12	x						501,900	455,100				455,100		455,100	82
9,150	13.4	13	x						611,900	565,500				565,500		565,500	82
9,590	14.4	14	x						597,900	551,000				551,000		551,000	82
9,710	15.3	15	x						577,700	526,700				526,700		526,700	82
10,000	16.0	16	x						568,600	518,200				518,200		518,200	82
9,760	14.1	17	x		x				628,500	202,600		371,200		573,800		573,800	80
9,130	13.1	18			x				652,600			580,100		580,100		580,100	81
9,600	14.2	19			x				632,600			561,300		561,300		561,300	81
9,310	14.2	20			x				606,900			542,600		542,600		542,600	81
9,160	14.3	21			x				594,800			532,200		532,200		532,200	81
10,040	14.6	22			x				640,300			571,700		571,700		571,700	81
10,030	14.4	23			x				647,900			579,200		579,200		579,200	81
9,170	13.5	24			x				626,900			562,700		562,700		562,700	81
8,190	12.4	25			x				614,800			549,100		549,100		549,100	81
9,370	13.2	26			x				662,300			587,500		587,500		587,500	81
8,810	12.3	27			x				667,600			595,100		595,100		595,100	81
8,930	12.5	28			x				668,700			593,100		593,100		593,100	81
8,360	12.5	29			x				619,000			556,100		556,100		556,100	81
8,360	12.7	30			x				610,800			547,600		547,600		547,600	81
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283,740	15.1									6,790,900	0	7,729,500	1,123,700	15,644,100	0	15,644,100	

Makeup Water	%	oct 2012	#7	#8	#1	#2	HRS. on OIL	OIL Gals.	GAS FEET M.	No. 7 Steam Lbs.	No. 8 Steam Lbs.	No. 1 Steam Lbs.	No. 2 Steam Lbs.	By GAS STEAM LBS.	By OIL STEAM LBS.	TOTAL STEAM GENERATED	BOILER EFF.
8,390	12.9	1		x	x				643,000		316,800	221,600		538,400		538,400	83
8,550	12.9	2		x					663,500		549,700			549,700		549,700	83
8,890	13.7	3		x					652,900		538,900			538,900		538,900	83
9,760	13.5	4		x					727,700		600,500			600,500		600,500	83
13,490	15.5	5		x					873,500		721,000			721,000		721,000	84
15,650	17.7	6		x					882,400		733,400			733,400		733,400	83
15,250	17.8	7		x					851,300		710,000			710,000		710,000	83
14,430	16.8	8		x					858,100		712,800			712,800		712,800	83
13,590	15.9	9		x					854,900		710,700			710,700		710,700	83
15,350	16.2	10	x	x					951,400	12,900	775,700			788,600		788,600	83
10,780	13.3	11		x					800,800		672,000			672,000		672,000	83
14,290	16.6	12		x					854,000		715,900			715,900		715,900	83
9,260	13.2	13		x					695,100		583,400			583,400		583,400	83
8,720	12.8	14		x					670,700		565,300			565,300		565,300	83
8,380	10.7	15		x		x			745,600		303,700		346,700	650,400		650,400	81
9,770	13.4	16				x			596,200				605,400	605,400		605,400	81
9,730	12.7	17				x			711,600				638,000	638,000		638,000	82
16,200	16.8	18			x	x			904,200			41,700	759,700	801,400		801,400	82
17,250	18.4	19			x	x			855,300			241,000	538,400	779,400		779,400	81
12,750	14.9	20			x	x			778,800			186,000	523,900	709,900		709,900	82
9,900	13.9	21				x			656,300				592,800	592,800		592,800	81
9,530	13.1	22				x			667,600				601,900	601,900		601,900	82
9,900	13.9	23				x			608,500				589,700	589,700		589,700	81
8,790	12.4	24				x			657,500				590,500	590,500		590,500	82
16,980	18.0	25	x		x				818,100	564,300		216,900		781,200		781,200	81
20,740	17.0	26	x		x				1,023,300	636,200		375,900		1,012,100		1,012,100	81
24,990	20.8	27	x		x				1,017,700	503,500		495,100		998,600		998,600	81
23,680	21.0	28	x		x				1,011,700	474,000		463,400		937,400		937,400	81
22,120	18.9	29	x		x				1,011,900	476,300		495,500		971,800		971,800	81
19,390	17.5	30	x		x				994,000	470,400		448,300		918,700		918,700	81
19,000	18.3	31	x		x				929,100	633,400		230,000		863,400		863,400	81
425,500	15.9									3,771,000	9,209,800	3,415,400	5,787,000	22,183,200	0	22,183,200	

Makeup Water	%	nov 2012	#7	#8	#1	#2	HRS. on OIL	OIL Gals.	GAS FEET M.	No. 7 Steam Lbs.	No. 8 Steam Lbs.	No. 1 Steam Lbs.	No. 2 Steam Lbs.	By GAS STEAM LBS.	By OIL STEAM LBS.	TOTAL STEAM GENERATED	BOILER EFF.
13,100	15.2	1	x						765,300	715,700				715,700		715,700	83
13,500	15.1	2	x						791,800	739,800				739,800		739,800	83
17,230	17.6	3	x		x				862,000	575,200		239,300		814,500		814,500	81
17,250	17.9	4	x		x				854,000	578,400		223,700		802,100		802,100	80
15,500	14.1	5	x		x				975,500	712,500		201,800		914,300		914,300	80
17,440	18.1	6	x		x				825,800	662,600		139,100		801,700		801,700	83
19,790	17.9	7	x		x				995,000	886,500		30,900		917,400		917,400	83
16,860	17.9	8	x						846,300	783,400				783,400		783,400	83
13,820	17.1	9	x						713,800	671,700				671,700		671,700	82
11,960	17.1	10	x						619,100	581,900				581,900		581,900	82
22,510	19.1	11	x		x				1,047,300	631,800		348,800		980,600		980,600	80
26,310	18.7	12	x		x				1,186,900	585,400		579,700		1,165,100		1,165,100	82
23,580	19.2	13	x	x	x				1,061,000	243,500	252,900	520,600		1,017,000		1,017,000	82
20,260	16.6	14		x	x	x			1,103,200		515,500	250,500	244,500	1,010,500		1,010,500	82
21,250	17.6	15		x		x			1,121,000		512,500		489,700	1,002,200		1,002,200	82
22,570	19.5	16		x		x			1,097,300		501,200		461,400	962,600		962,600	81
18,860	17.6	17		x		x			1,015,300		475,400		412,200	887,600		887,600	82
17,720	17.4	18		x		x			996,400		611,900		231,800	843,700		843,700	79
14,850	15.2	19		x		x			959,200		766,900		42,300	809,200		809,200	83
16,080	15.6	20		x		x			1,008,300		810,400		47,700	858,100		858,100	83
13,500	14.5	21		x		x			908,600		735,500		35,900	771,400		771,400	83
10,850	13.6	22		x					786,300		661,000			661,000		661,000	83
21,140	16.5	23		x		x			1,188,100		623,900		438,800	1,062,700		1,062,700	80
20,180	16.0	24		x		x			1,187,600		529,200		515,700	1,044,900		1,044,900	82
20,510	18.5	25		x		x			1,051,700		479,200		442,100	921,300		921,300	81
23,940	16.1	26		x		x			1,404,500		610,800		627,100	1,237,900		1,237,900	83
26,820	17.7	27		x		x			1,431,700		628,800		629,600	1,258,400		1,258,400	82
21,790	16.6	28		x		x			1,242,600		564,700		524,200	1,088,900		1,088,900	81
17,140	16.3	29	x	x		x			1,005,800	312,400	275,700		282,700	870,800		870,800	77
16,230	15.8	30	x			x			904,800	797,600			57,300	854,900		854,900	83
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552,540	17.0									9,478,400	9,555,500	2,534,400	5,483,000	27,051,300	0	27,051,300	

Makeup Water	%	dec 2012	#7	#8	#1	#2	HRS. on OIL	OIL Gals.	GAS FEET M.	No. 7 Steam Lbs.	No. 8 Steam Lbs.	No. 1 Steam Lbs.	No. 2 Steam Lbs.	By GAS STEAM LBS.	By OIL STEAM LBS.	TOTAL STEAM GENERATED	BOILER EFF.
12,030	14.1	1	x						735,800	706,100				706,100		706,100	82
13,180	14.6	2	x						783,300	749,800				749,800		749,800	83
14,060	17.0	3	x						717,900	687,300				687,300		687,300	82
18,850	17.8	4	x		x				877,100	788,000		88,900		876,900		876,900	83
20,670	18.9	5	x			x			946,400	828,000			78,500	906,500		906,500	83
23,500	21.4	6	x						974,800	909,600				909,600		909,600	83
19,000	17.3	7	x			x			994,600	603,100			309,300	912,400		912,400	82
20,100	17.3	8	x			x			1,038,000	487,100			479,300	966,400		966,400	82
21,830	16.8	9	x			x			1,142,500	535,200			542,400	1,077,600		1,077,600	82
31,180	18.4	10	x			x			1,508,500	713,400			692,000	1,405,400		1,405,400	81
34,250	22.3	11	x			x			1,357,800	663,300			611,500	1,274,800		1,274,800	81
25,030	17.5	12	x			x			1,257,400	609,200			578,700	1,187,900		1,187,900	81
23,450	18.4	13	x			x			1,119,900	546,000			512,500	1,058,500		1,058,500	81
21,800	18.1	14	x			x			1,059,000	518,200			480,800	999,000		999,000	81
19,200	17.9	15	x			x			943,000	452,100			435,900	888,000		888,000	81
22,100	16.9	16	x			x			1,155,200	544,500			539,000	1,083,500		1,083,500	81
21,180	16.5	17	x	x		x			1,140,700	230,000	281,600		553,300	1,064,900		1,064,900	81
21,760	18.2	18		x		x			1,138,300		492,500		501,700	994,200		994,200	81
21,630	16.5	19		x		x			1,236,500		492,600		592,400	1,085,000		1,085,000	82
26,030	16.0	20		x		x			1,543,400		614,800		737,700	1,352,500		1,352,500	82
25,950	16.1	21		x		x			1,514,200		627,000		710,900	1,337,900		1,337,900	83
24,820	19.6	22	x	x		x			1,208,500	282,700	474,800		294,500	1,052,000		1,052,000	83
27,670	18.8	23	x	x					1,329,600	686,900	536,600			1,223,500		1,223,500	83
30,710	18.5	24	x	x					1,501,200	783,100	594,000			1,377,100		1,377,100	83
34,310	19.2	25	x	x					1,612,200	846,800	633,000			1,479,800		1,479,800	82
35,390	18.8	26	x	x					1,719,700	834,500	724,600			1,559,100		1,559,100	83
29,700	18.1	27	x	x					1,504,000	723,500	639,000			1,362,500		1,362,500	83
25,970	16.2	28	x	x					1,462,300	706,400	625,300			1,331,700		1,331,700	83
26,210	16.7	29	x	x					1,425,600	686,500	612,300			1,298,800		1,298,800	83
28,180	19.3	30	x	x					1,327,400	624,400	589,500			1,213,900		1,213,900	83
28,840	18.0	31	x	x					1,470,600	686,400	643,700			1,330,100		1,330,100	83
748,580	17.9									17,432,100	8,581,300	88,900	8,650,400	34,752,700	0	34,752,700	

Makeup Water	%	jan 2013	#7	#8	#1	#2	HRS. on OIL	OIL Gals.	GAS FEET M.	No. 7 Steam Lbs.	No. 8 Steam Lbs.	No. 1 Steam Lbs.	No. 2 Steam Lbs.	By GAS STEAM LBS.	By OIL STEAM LBS.	TOTAL STEAM GENERATED	BOILER EFF.
31,330	16.0	1	x	x					1,479,900	963,200	660,700			1,623,900		1,623,900	82
31,160	17.7	2	x	x					1,595,600	751,800	706,100			1,457,900		1,457,900	83
27,690	18.4	3	x	x					1,466,900	588,100	657,600			1,245,700		1,245,700	82
28,500	18.6	4	x	x					1,395,600	628,400	641,500			1,269,900		1,269,900	83
23,520	17.4	5	x	x					1,231,100	539,000	580,400			1,119,400		1,119,400	83
26,000	17.8	6	x	x					1,326,500	596,600	614,900			1,211,500		1,211,500	83
25,650	17.8	7	x	x		x			1,294,000	595,600	369,200		233,600	1,198,400		1,198,400	80
22,070	17.2	8	x			x			1,133,100	542,300			525,100	1,067,400		1,067,400	81
24,000	18.3	9	x			x			1,151,000	555,100			535,000	1,090,100		1,090,100	82
28,990	22.4	10	x			x			1,142,200	547,100			527,300	1,074,400		1,074,400	81
18,690	17.9	11	x			x			916,300	676,400			190,700	867,100		867,100	81
24,680	16.8	12	x			x			1,286,900	707,800			512,700	1,220,500		1,220,500	82
30,380	18.1	13	x			x			1,482,500	701,000			691,100	1,392,100		1,392,100	82
29,630	16.5	14	x			x			1,596,500	750,600			742,900	1,493,500		1,493,500	83
32,790	18.7	15	x			x			1,568,000	742,100			714,700	1,456,800		1,456,800	82
27,360	17.6	16	x			x			1,367,200	669,300			618,300	1,287,600		1,287,600	81
25,890	18.1	17	x			x			1,239,800	626,100			560,400	1,186,500		1,186,500	82
26,050	20.6	18	x			x			1,105,100	766,700			281,800	1,048,500		1,048,500	81
25,750	23.6	19	x						955,000	905,300				905,300		905,300	83
31,510	23.1	20	x	x					1,308,700	674,300	459,600			1,133,900		1,133,900	82
36,760	20.8	21	x	x					1,601,400	747,600	715,800			1,463,400		1,463,400	83
36,500	20.5	22	x	x					1,645,600	739,600	741,600			1,481,200		1,481,200	83
27,400	16.9	23	x	x		x			1,471,700	389,400	670,900		288,900	1,349,200		1,349,200	82
32,200	19.0	24		x		x			1,707,600		664,300		743,900	1,408,200		1,408,200	80
27,930	18.2	25		x		x			1,447,600		663,800		607,500	1,271,300		1,271,300	81
22,000	17.6	26		x		x			1,168,500		548,900		488,800	1,037,700		1,037,700	81
17,450	16.1	27		x		x			934,000		574,500		325,000	899,500		899,500	82
14,520	16.3	28		x					872,600		740,100			740,100		740,100	80
19,920	16.8	29		x		x			1,132,300		602,800		381,500	984,300		984,300	83
25,670	16.2	30		x		x			1,484,400		653,800		665,300	1,319,100		1,319,100	82
27,940	15.6	31		x		x			1,692,500		741,300		747,800	1,489,100		1,489,100	83
829,930	18.2									15,403,400	12,007,800	0	10,382,300	37,793,500	0	37,793,500	

Makeup Water	%	feb 2013	#7	#8	#1	#2	HRS. on OIL	OIL Gals.	GAS FEET M.	No. 7 Steam Lbs.	No. 8 Steam Lbs.	No. 1 Steam Lbs.	No. 2 Steam Lbs.	By GAS STEAM LBS.	By OIL STEAM LBS.	TOTAL STEAM GENERATED	BOILER EFF.
29,430	16.0	1		x		x			1,748,700		772,800		757,800	1,530,600		1,530,600	81
26,710	19.3	2		x		x			1,306,000		619,000		529,500	1,148,500		1,148,500	81
24,460	19.4	3		x		x			1,179,800		565,100		481,800	1,046,900		1,046,900	81
26,240	19.3	4		x		x			1,280,000		580,000		545,800	1,125,800		1,125,800	81
25,100	19.3	5		x		x			1,233,600		561,800		518,500	1,080,300		1,080,300	82
26,330	23.9	6		x		x			1,058,000		659,200		255,800	915,000		915,000	83
22,960	19.8	7	x	x	x				1,061,100	377,700	480,600	102,300		960,600		960,600	83
27,050	21.5	8	x		x	x			1,099,000	553,600		429,900	59,000	1,042,500		1,042,500	83
29,030	23.1	9	x		x				1,101,600	541,700		503,600		1,045,300		1,045,300	82
26,060	22.3	10	x		x				1,029,300	492,700		479,400		972,100		972,100	82
30,290	22.1	11	x		x				1,202,600	570,100		566,200		1,136,300		1,136,300	82
32,040	26.3	12	x		x				1,269,900	592,300		420,600		1,012,900		1,012,900	81
28,520	21.9	13	x						1,151,400	766,200		312,700		1,078,900		1,078,900	81
25,540	21.6	14	x		x				1,003,400	749,100		231,900		981,000		981,000	82
34,700	23.2	15	x		x				1,327,800	622,400		619,700		1,242,100		1,242,100	82
30,590	21.2	16	x	x	x				1,302,600	606,000	582,300	8,000		1,196,300		1,196,300	81
31,020	26.2	17	x	x					1,070,100	682,800	301,500			984,300		984,300	83
30,500	24.6	18	x		x				1,113,700	722,100		307,300		1,029,400		1,029,400	82
38,060	23.9	19	x		x				1,407,800	676,300		642,800		1,319,100		1,319,100	82
39,510	22.4	20	x		x				1,567,600	742,400		720,000		1,462,400		1,462,400	82
39,350	22.0	21	x		x				1,604,400	749,500		733,400		1,482,900		1,482,900	82
38,180	22.0	22	x		x				1,556,500	730,900		712,300		1,443,200		1,443,200	82
35,660	21.6	23	x		x				1,465,500	691,200		679,100		1,370,300		1,370,300	82
33,550	23.9	24	x		x				1,232,200	588,800		575,700		1,164,500		1,164,500	82
39,120	26.7	25	x	x	x				1,404,100	392,400	184,900	637,700		1,215,000		1,215,000	83
38,440	24.1	26		x	x				1,518,000		654,500	668,000		1,322,500		1,322,500	83
40,120	26.1	27		x	x				1,463,700		638,300	638,700		1,277,000		1,277,000	83
42,230	27.0	28	x	x	x				1,458,400	421,900	649,700	226,400		1,298,000		1,298,000	82
	#DIV/0!	29												0		0	
	#DIV/0!	30												0		0	
	#DIV/0!	31												0		0	
890,790	22.5									12,270,100	7,249,700	10,215,700	3,148,200	32,883,700	0	32,883,700	

Average Of Steam Produced (lbs)
Monthly average
1,174,418

Average during Feb 15 through 18
1,113,025

Makeup Water	%	mar 2013	#7	#8	#1	#2	HRS. on OIL	OIL Gals.	GAS FEET M.	No. 7 Steam Lbs.	No. 8 Steam Lbs.	No. 1 Steam Lbs.	No. 2 Steam Lbs.	By GAS STEAM LBS.	By OIL STEAM LBS.	TOTAL STEAM GENERATED	BOILER EFF.
41,710	25.5	1	x	x					1,494,300	699,600	656,000			1,355,600		1,355,600	82
38,800	25.5	2	x	x					1,390,600	634,900	627,400			1,262,300		1,262,300	82
33,970	24.4	3	x	x					1,264,300	572,900	580,600			1,153,500		1,153,500	82
35,150	26.5	4	x	x					1,218,900	543,200	559,700			1,102,900		1,102,900	82
34,560	22.9	5	x	x	x				1,497,000	361,600	620,500	269,400		1,251,500		1,251,500	82
39,990	26.8	6	x	x					1,370,500	608,700	628,600			1,237,300		1,237,300	81
34,330	25.0	7	x	x					1,258,600	462,600	679,000			1,141,600		1,141,600	82
25,400	26.4	8	x	x		x			876,200	375,400	224,500		197,700	797,600		797,600	82
25,240	26.9	9	x			x			863,700	391,900			387,600	779,500		779,500	81
30,060	25.1	10	x			x			1,067,400	492,400			500,900	993,300		993,300	81
42,740	28.2	11	x			x			1,350,300	621,700			634,900	1,256,600		1,256,600	82
39,000	28.7	12	x			x			1,212,200	569,500			559,800	1,129,300		1,129,300	82
38,140	27.3	13	x			x			1,243,900	581,600			578,300	1,159,900		1,159,900	83
21,470	12.1	14	x	x		x			2,212,700	820,700	182,100		465,400	1,468,200		1,468,200	82
14,240	15.9	15		x		x			830,900		205,300		536,700	742,000		742,000	81
20,800	12.8	16		x		x			1,878,700		457,300		893,700	1,351,000		1,351,000	82
23,920	18.6	17		x		x			1,152,900		545,300		519,900	1,065,200		1,065,200	81
20,930	17.6	18		x		x			1,052,244		703,600		285,400	989,000		989,000	82
21,930	17.3	19	x	x		x			1,151,400	266,900	642,300		143,300	1,052,500		1,052,500	82
30,010	21.3	20	x	x		x			1,287,800	369,500	591,400		209,600	1,170,500		1,170,500	82
32,890	18.2	21		x		x			1,629,200		670,000		831,000	1,501,000		1,501,000	82
34,820	22.7	22		x		x			1,447,700		652,300		622,900	1,275,200		1,275,200	82
35,470	24.7	23		x		x			1,345,800		619,900		572,600	1,192,500		1,192,500	82
35,680	22.9	24		x		x			1,458,600		659,100		634,000	1,293,100		1,293,100	82
39,780	25.8	25		x		x			1,411,400		666,800		612,700	1,279,500		1,279,500	82
35,620	22.6	26		x		x			1,481,000		658,400		648,400	1,306,800		1,306,800	82
40,700	29.3	27		x		x			1,298,100		595,100		556,700	1,151,800		1,151,800	83
22,880	21.0	28		x		x			1,038,300		695,800		210,000	905,800		905,800	81
20,010	21.8	29		x		x			912,200		724,900		37,400	762,300		762,300	82
15,930	19.7	30		x					783,400		670,100			670,100		670,100	82
18,350	21.6	31		x					824,900		704,200			704,200		704,200	82
944,520	22.7									8,373,100	15,220,200	269,400	10,638,900	34,501,600	0	34,501,600	

Average Of Steam Produced (lbs)
Monthly average
1,112,955

Average for period in which data was recorded (lbs)
1,194,378

Makeup Water	%	apr 2013	#7	#8	#1	#2	HRS. on OIL	OIL Gals.	GAS FEET M.	No. 7 Steam Lbs.	No. 8 Steam Lbs.	No. 1 Steam Lbs.	No. 2 Steam Lbs.	By GAS STEAM LBS.	By OIL STEAM LBS.	TOTAL STEAM GENERATED	BOILER EFF.
26,910	22.2	1		x		x			1,159,800		696,900		307,500	1,004,400		1,004,400	82
25,140	18.5	2		x		x			1,276,500		603,800		523,900	1,127,700		1,127,700	82
26,930	21.6	3		x		x			1,097,800		555,400		479,600	1,035,000		1,035,000	81
24,930	22.3	4		x		x			986,900		286,200	224,900	418,400	929,500		929,500	82
17,400	18.4	5				x			825,900			593,800	192,700	786,500		786,500	83
14,180	18.5	6				x			662,200			637,300		637,300		637,300	82
13,480	17.7	7				x			657,400			631,700		631,700		631,700	81
15,310	20.0	8			x	x			671,400			403,300	232,200	635,500		635,500	81
18,790	23.4	9			x	x			745,200			160,400	507,000	667,400		667,400	82
22,880	19.2	10			x	x			1,097,000			497,900	493,700	991,600		991,600	83
26,420	20.2	11			x	x			1,200,300			544,300	541,700	1,086,000		1,086,000	82
25,840	21.1	12			x	x			1,122,200			509,400	507,400	1,016,800		1,016,800	891
20,560	20.9	13			x	x			893,100			496,000	319,400	815,400		815,400	82
15,400	19.9	14			x				715,300			643,900		643,900		643,900	82
23,680	22.1	15			x	x			988,900			625,600	263,800	889,400		889,400	82
23,410	19.8	16		x	x				1,011,700		279,200	486,200	215,300	980,700		980,700	82
19,910	18.4	17		x	x				1,068,500		897,500	2,700		900,200		900,200	82
24,780	19.6	18		x	x				1,078,500		672,100	374,600		1,046,700		1,046,700	81
25,320	21.5	19		x	x	x			1,095,200		324,100	117,600	537,200	978,900		978,900	81
25,340	22.9	20			x	x			1,002,300			526,800	389,900	916,700		916,700	82
17,980	20.1	21			x				830,500			743,600		743,600		743,600	83
20,680	21.2	22			x	x			883,900			607,800	203,500	811,300		811,300	82
27,880	20.4	23			x	x			1,265,600			566,500	569,900	1,136,400		1,136,400	81
29,110	23.2	24			x	x			1,140,500			518,800	522,400	1,041,200		1,041,200	81
22,320	28.5	25			x				608,700			649,000		649,000		649,000	83
19,520	18.4	26			x				916,400			879,900		879,900		879,900	82
20,850	20.8	27			x				935,200			830,600		830,600		830,600	82
15,360	17.8	28			x				799,600			714,900		714,900		714,900	81
14,470	18.9	29			x				711,800			636,700		636,700		636,700	81
27,610	36.9	30			x				696,400			621,600		621,600		621,600	81
	#DIV/0!	31												0		0	
652,390	21.0									0	4,315,200	14,245,800	7,225,500	25,786,500	0	25,786,500	

Average Of Steam Produced (lbs)
Monthly average
859,550

Average for April 30th (lbs)
621,600

Makeup Water	%	may 2013	#7	#8	#1	#2	HRS. on OIL	OIL Gals.	GAS FEET M.	No. 7 Steam Lbs.	No. 8 Steam Lbs.	No. 1 Steam Lbs.	No. 2 Steam Lbs.	By GAS STEAM LBS.	By OIL STEAM LBS.	TOTAL STEAM GENERATED	BOILER EFF.
18,160	21.9	1		x	x				782,100		91,000	596,500		687,500		687,500	81
29,280	26.7	2	x	x	x				1,165,800	213,900	146,500	549,400		909,800		909,800	79
23,080	19.2	3	x		x	x			1,073,000	496,600		377,600	125,900	1,000,100		1,000,100	79
21,740	19.2	4	x			x			1,015,300	468,800			470,700	939,500		939,500	81
20,550	22.1	5	x			x			817,100	764,300			8,100	772,400		772,400	82
15,250	17.6	6	x						765,200	720,800				720,800		720,800	83
15,230	19.5	7	x						692,700	648,400				648,400		648,400	82
13,990	19.2	8	x						650,000	604,300				604,300		604,300	82
16,080	21.8	9	x						656,300	613,300				613,300		613,300	81
14,850	19.5	10	x						674,800	631,400				631,400		631,400	83
15,320	20.8	11	x						645,300	610,400				610,400		610,400	81
16,960	21.3	12	x						698,300	661,400				661,400		661,400	82
14,090	19.1	13	x			x			680,300	293,100			319,400	612,500		612,500	81
13,850	20.7	14				x			613,100				555,800	555,800		555,800	82
16,130	22.7	15				x			654,000				589,100	589,100		589,100	82
14,060	20.5	16				x			632,000				570,100	570,100		570,100	82
11,790	17.3	17				x			633,100				567,100	567,100		567,100	81
12,240	19.9	18				x			565,200				511,100	511,100		511,100	82
8,510	17.4	19				x			434,600				406,400	406,400		406,400	81
	######	20												0		0	
	######	21												0		0	
	######	22												0		0	
	######	23												0		0	
21,220	44.1	24	x		x				412,200	146,600		253,100		399,700		399,700	80
8,000	13.0	25			x				564,800			509,700		509,700		509,700	82
8,730	15.2	26			x				529,900			476,500		476,500		476,500	81
8,020	13.3	27			x				555,500			500,200		500,200		500,200	81
9,690	15.6	28			x				575,900			514,400		514,400		514,400	81
9,350	15.0	29			x				579,200			517,700		517,700		517,700	82
9,570	14.8	30			x				620,300			536,900		536,900		536,900	83
10,920	16.9	31			x				620,900			537,400		537,400		537,400	82
396,660	19.8									6,873,300	237,500	5,369,400	4,123,700	16,603,900	0	16,603,900	

Average Of Steam Produced (lbs)
Monthly average
614,959

Average for May 1st (lbs)
687,500

Appendix F: Derivation of Hydraulic Power Equation

1/1

Derivation of Pump Hydraulic Power Equation Expressed in HP:

Known: $\text{Power} = \frac{\text{Work}}{\text{Time}} = \dot{W}$ Work can be expressed in: in-lbs

$1 \text{ Gallon} = 231 \text{ in}^3$

$1 \text{ HP} = 33{,}000 \frac{\text{ft-lbs}}{\text{min}}$

$$\text{Power}\left(\frac{\text{in-lbs}}{\text{min}}\right) = \text{Flow}\left(\frac{\text{in}^3}{\text{min}}\right) \times \text{Pressure}\left(\frac{\text{lbs}}{\text{in}^2}\right) \quad (1)$$

Converting $33{,}000 \frac{\text{ft-lbs}}{\text{min}}$ to $\frac{\text{in-lbs}}{\text{min}}$

$$33{,}000 \frac{\text{ft-lbs}}{\text{min}} \cdot \frac{12 \text{ in}}{1 \text{ ft}} \Rightarrow 396{,}000 \frac{\text{in-lbs}}{\text{min}} = 1 \text{ HP}$$

$$\text{Flow}\left(\frac{\text{in}^3}{\text{min}}\right) = \text{Flow}\left(\frac{\text{gal}}{\text{min}}\right) \times 231\left(\frac{\text{in}^3}{\text{gal}}\right) \quad (2)$$

Converting Equation (1) into HP units
Sub. (2) into (1)

$$1 \text{ HP} = 396{,}000 \frac{\text{in-lbs}}{\text{min}} = \text{Flow}\left(\frac{\text{gal}}{\text{min}}\right) \times 231\left(\frac{\text{in}^3}{\text{gal}}\right) \times \text{Pressure}\left(\frac{\text{lbs}}{\text{in}^2}\right)$$

$$\Rightarrow \frac{396{,}000 \frac{\text{in-lbs}}{\text{min}}}{231\left(\frac{\text{in}^3}{\text{gal}}\right)} = \text{Flow}\left(\frac{\text{gal}}{\text{min}}\right) \times \text{Pressure}\left(\frac{\text{lbs}}{\text{in}^2}\right)$$

$$\Rightarrow 1714.29 \frac{\text{gal}}{\text{min}} \cdot \frac{\text{lbs}}{\text{in}^2} = \text{Flow}\left(\frac{\text{gal}}{\text{min}}\right) \times \text{Pressure}\left(\frac{\text{lbs}}{\text{in}^2}\right)$$

↳ This becomes the units conversion factor for the equation

$$\therefore \text{Pump Power in HP} = \frac{\text{Flow (GPM)} \times \text{Pressure (PSI)}}{1714.29} \Leftarrow \text{Assuming 100\% efficiency}$$

$$\Rightarrow \text{Pump } \dot{W} \text{ (HP)} = \frac{\text{Flow (GPM)} \times \text{Pressure (PSI)}}{(1714.29 \times \eta)}$$

where η = Pump efficiency

Appendix G: Case 1 Energy Consumption Hand Calculations

1/4

Case 1:

a) Energy consumption estimate calculations for months w/ recorded power consumption data:

1) February 2012: Total Steam Generated = 31,720,400 lbs

For CRE15-3:

Avg Power Consumption = 5.280336 kW

$29 \text{ days} \times \frac{24 \text{ hour}}{1 \text{ day}} = 696 \text{ hours}$

∴ Avg Month Energy consumption (kWh) in Feb. 2012 = (5.28 kW) × (696 hours)

Avg En. Cons. = 3675.11 kWh For CRE15-3

For Worthington D-824:

Avg Power Consumption = 6.117176 kW

Avg. Month Energy Consumption = (6.12 kW) × (696 hours)
= 4257.555 kWh.

2) March 2012: Total Steam Generated = 22,454,400 lbs

For CRE 15-3:

Avg Power Consumption = 6.642080 KW

$31 \text{ days} \times \frac{24 \text{ hours}}{1 \text{ day}} = 744 \text{ hours}$

Avg. Month Energy Consumption (kWh) = (6.642 kW) × (744 hours)
= 4941.71 kWh

For Worthington D-824:

Avg. Power Consumption = 6.140988 kW

Avg. Month Energy consumption = (6.141 kW) × (744 hours)
= 4568.895 kWh

3) April 2012: Total Steam Generated = 18,715,700 lbs

For CRE-15:

Avg. Power Consumption = 5.188014 KW

$30 \text{ days} \times \frac{24 \text{ hours}}{1 \text{ day}} = 720 \text{ hours}$

Avg. Month Energy consumption (kWh) = (5.188 kW) × (720 hours)
= 3735.37 kWh.

For Worthington D-824:

Avg. Power Consumption = 5.816223 KW

Avg. Month Energy Consumption = (5.816 kW) × (720 hours)
= 4187.68 kWh.

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Case1 Continued:

b) Energy Consumption estimate calculations for months without recorded power consumption data: based on Steam Generation Ratios:

1) May 2012:
Total Steam Generated (May) = 13,620,200 lbs

Since May has 31 days, using March information (31 days) to find energy consumption estimate for the month of may.

For CRE 15-3:

$$\text{May Energy consumption Estimate} = (4941.71\ \text{kWh}) \times \left(\frac{13{,}620{,}200\ \text{lbs}}{22{,}454{,}400\ \text{lbs}}\right) = 2997.5\ \text{kWh}$$

For Worthington D-824

$$\text{May Energy consumption Estimate} = (4568.895\ \text{Kwh}) \times \left(\frac{13{,}620{,}200\ \text{lbs.}}{22{,}454{,}400\ \text{lbs}}\right) = 2771.36\ \text{KWh}$$

2) June 2012: ToTal Steam Generated = 14,020,700 lbs
Since June has 30 days, using April information (30 days) to find energy consumption estimate for the month of June

For CRE 15-3:

$$\text{June Energy consumption Estimate} = (3735.37\ \text{KWh}) \times \left(\frac{14{,}020{,}700\ \text{lbs.}}{18{,}715{,}700\ \text{lbs.}}\right) = 2798.32\ \text{KWh}$$

For Worthington D-824:

$$\text{June Energy Consumption Estimate} = (4187.68\ \text{KWh}) \times \left(\frac{14{,}020{,}700\ \text{lbs}}{18{,}715{,}700\ \text{lbs}}\right) = 3137.16\ \text{kWh}$$

3) July 2012: Total steam Generated = 12,954,101 lbs.

For CRE 15-3:

$$\text{July Energy Consumption Estimate} = (4941.71\ \text{KWh}) \times \left(\frac{12{,}954{,}101\ \text{lbs.}}{22{,}454{,}400\ \text{lbs}}\right) = 2850.91\ \text{KWh}$$

For Worthington D-824

$$\text{July Energy Consumption Estimate} = (4568.895\ \text{KWh}) \times \left(\frac{12{,}954{,}101\ \text{lbs}}{22{,}454{,}400\ \text{lbs}}\right) = 2635.83\ \text{KWh}$$

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Case 1 Continued:

4) August 2012: Total Steam Generated = 14,783,000 lbs

For CRE 15-3:

August Energy consumption Estimate $= (4941.71\ kWh) \times \left(\frac{14,783,000\ lbs}{22,454,400\ lbs}\right)$

$= 3253.41\ kWh$

For Worthington D-824

August Energy consumption Energy $= (4568.895\ kWh) \times \left(\frac{14,783,000\ lbs}{22,454,400\ lbs}\right)$

$= 3007.96\ kWh$

5) September 2012: Total Steam Generated = 15,644,100 lbs

For CRE 15-3:

September Energy Consumption Estimate $= (3735.37\ kWh) \times \left(\frac{15,644,100\ lbs}{18,715,700\ lbs}\right)$

$= 3122.33\ kWh$

For Worthington D-824

September Energy Consumption Estimate $= (4187.68\ kWh) \times \left(\frac{15,644,100\ lbs}{18,715,700\ lbs}\right)$

$= 3500.4\ kWh$

6) October 2012: Total Steam Generated = 22,183,200 lbs

For CRE 15-3:

October Energy consumption Estimate $= (4941.71\ kWh) \times \left(\frac{22,183,200\ lbs}{22,454,400\ lbs}\right)$

$= 4882.02\ kWh$

For Worthington D-824

October Energy consumption Estimate $= (4568.895\ kWh) \times \left(\frac{22,183,200\ lbs}{22,454,400\ lbs}\right)$

$= 4513.71\ kWh$

7) November 2012: Total Steam Generated = 27,051,300 lbs

For CRE 15-3:

November Energy Consumption Estimate $= (3735.37\ kWh) \times \left(\frac{27,051,300\ lbs}{18,715,700\ lbs}\right)$

$= 5399.03\ kWh$

For Worthington D-824

November Energy Consumption Estimate $= (4187.68\ kWh) \times \left(\frac{27,051,300\ lbs}{18,715,700\ lbs}\right)$

$= 6052.79\ kWh$

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Case 1 continued :

8) December 2012 : Total Steam Generated = 34,752,700 lbs

For CRE 15-3:

December Energy Consumption Estimate = $(4941.71 \text{ KWh}) \times \left(\frac{34,752,700 \text{ lbs}}{22,454,400 \text{ lbs}}\right)$

= 7648.29 KWh

For Worthington D-824:

December Energy Consumption Estimate = $(4568.895 \text{ kWh}) \times \left(\frac{34,752,700 \text{ lbs}}{22,454,400 \text{ lbs}}\right)$

= 7071.28 kWh

9) January 2013 : Total Steam Generated = 37,793,500 lbs

For CRE 15-3:

January Energy Consumption Estimate = $(4941.71 \text{ kWh}) \times \left(\frac{37,793,500 \text{ lbs}}{22,454,400 \text{ lbs}}\right)$

= 8317.5 kWh

For Worthington D-824

January Energy Consumption Estimate = $(4568.895 \text{ kWh}) \times \left(\frac{37,793,500 \text{ lbs}}{22,454,400 \text{ lbs}}\right)$

= 7690.01 kWh

Based on calculations shown above

Estimated Annual Energy Consumption for CRE 15-3 = 53621.5 kWh

Estimated Annual Energy consumption for Worthington D-824 = 53394.63 kWh

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Appendix H: Case 2 Energy Consumption Hand Calculations

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Case 2:

a) Energy consumption Estimate calculations for month with recorded power consumption data:

1) April 2013: Total Steam Generated = 25,786,500 lbs

For CRE 15-3:

Using Data during time the Heat exchanger valve was closed:

April 15 - April 18 Avg. Power consumption = 3.010338 kW

Estimated Avg. Month Energy Consumption = (3.010338 kW) x (720 hours) = 2167.44 kWh

Data During Time the heat exchanger valve was open:

April 15 - April 18 Avg Power Consumption = 6.188008 kW

Estimated Avg. Month Energy Consumption = (6.188008 kW) x (720 hours) = 4455.37 kWh

For Worthington D-824:

Using data during time the heat exchanger valve was closed:

April 15-18 Avg. Power Consumption = 4.118026 kW

Estimated Avg. Month Energy consumption = (4.118026 kW) x (720 hours) = 2964.98 kWh

Using data when heat exchanger valve was open:

April 15-18 Avg. Power Consumption = 5.462907 kW

Estimated Avg. Month Energy Consumption = (5.462907 kW) x (720 hours) = 3933.29 kWh.

b) Energy Consumption estimate calculations for months without recorded power consumption data: Based on recorded data from April 2013 and steam Generation Ratios

1) May 2012: Total Steam Generated: 13,620,200 lbs

For CRE 15-3:

With Heat exchanger valve closed:

May Energy Consumption Estimate = $(2167.44 \text{ kWh}) \times \left(\frac{13{,}620{,}200 \text{ lbs}}{25{,}786{,}500 \text{ lbs}}\right)$ = 1144.82 kWh

With Heat exchanger valve open

May Energy consumption Estimate = $(4455.37 \text{ kWh}) \times \left(\frac{13{,}620{,}200 \text{ lbs}}{25{,}786{,}500 \text{ lbs}}\right)$ = 2353.29 kWh

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Case 2 Continued:

1) May 2012:

For Worthington D-824:

With heat exchanger valve closed

May Energy Consumption Estimate $= (2964.98\ kWh) \times \left(\frac{13{,}620{,}200\ lbs}{25{,}786{,}500\ lbs}\right)$

$= 1566.08\ kWh$

With heat exchanger Valve open

May Energy Consumption Estimate $= (3933.29\ kWh) \times \left(\frac{13{,}620{,}200\ lbs}{25{,}786{,}500\ lbs}\right)$

$= 2077.53\ kWh$

2) June 2012: Total Steam Generated = 14,020,700 lbs

For CRE 15-3:

with heat exchanger valve closed:

June energy consumption Estimate $= (2167.44\ kWh) \times \left(\frac{14{,}020{,}700\ lbs}{25{,}786{,}500\ lbs}\right)$

$= 1178.49\ kWh$

With heat exchanger Valve open:

June energy Consumption Estimate $= (4455.37\ kWh) \times \left(\frac{14{,}020{,}700\ lbs}{25{,}786{,}500\ lbs}\right)$

$= 2422.48\ kWh$

For Worthington D-824:

With heat exchanger valve closed

June energy consumption estimate $= (2964.68\ kWh) \times \left(\frac{14{,}020{,}700\ lbs}{25{,}786{,}500\ lbs}\right)$

$= 1611.96\ kWh$

With heat exchanger valve open

June energy consumption estimate $= (3933.29\ kWh)\left(\frac{14{,}020{,}700\ lbs}{25{,}786{,}500\ lbs}\right)$

$= 2138.62\ kWh$

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Case 2 continued:

3) July 2012: Total Steam Generated = 12,954,101 lbs

For CRE 15-3:

With heat exchanger valve closed:

$$\text{July energy consumption Estimate} = (2167.44\ kWh) \times \left(\frac{12,954,101\ lbs}{25,786,500\ lbs}\right) = 1088.83\ kWh$$

With heat exchanger valve open:

$$\text{July energy consumption Estimate} = (4455.37\ kWh) \times \left(\frac{12,954,101\ lbs}{25,786,500\ lbs}\right) = 2238.2\ kWh$$

For Worthington D-824,

With heat exchanger valve closed:

$$\text{July energy consumption Estimate} = (2964.68\ kWh) \times \left(\frac{12,954,101\ lbs}{25,786,500\ lbs}\right) = 1489.34\ kWh$$

With heat exchanger valve open:

$$\text{July energy consumption Estimate} = (3933.29\ kWh) \times \left(\frac{12,954,101\ lbs}{25,786,500\ lbs}\right) = 1975.93\ kWh$$

4) August 2012: Total Steam Generated = 14,783,000 lbs

For CRE 15-3:

With heat exchanger valve closed:

$$\text{August energy consumption estimate} = (2167.44\ kWh) \times \left(\frac{14,783,000\ lbs}{25,786,500\ lbs}\right) = 1242.56\ kWh$$

With heat exchanger valve open:

$$\text{August energy consumption estimate} = (4455.37\ kWh) \times \left(\frac{14,783,000\ lbs}{25,786,500\ lbs}\right) = 2554.19\ kWh$$

For Worthington D-824:

With heat exchanger valve closed:

$$\text{August energy consumption estimate} = (2964.68\ kWh) \times \left(\frac{14,783,000\ lbs}{25,786,500\ lbs}\right) = 1699.61\ kWh$$

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Case 2 Continued:

For Worthington D-824:

With heat exchanger valve open:

August energy consumption Estimate = (3933.29 kWh) x (14,783,000 lbs / 25,786,500 lbs)
= 2254.89 kWh

5) September 2012: Total Steam Generated = 15,644,100 lbs

For CRE 15-3:

With heat exchanger valve closed:

September energy consumption Estimate = (2167.44 kWh) x (15,644,100 lbs / 25,786,500 lbs)
= 1314.94 kWh

With heat exchanger valve open:

September energy consumption Estimate = (4455.37 kWh) x (15,644,100 lbs / 25,786,500 lbs)
= 2702.97 kWh

For Worthington D-824:

With heat exchanger valve closed:

September energy consumption Estimate = (2964.68 kWh) x (15,644,100 lbs / 25,786,500 lbs)
= 1798.61 kWh

With heat exchanger valve open:

September energy consumption Estimate = (3933.29 kWh) x (15,644,100 lbs / 25,786,500 lbs)
= 2386.24 kWh

6) October 2012: Total Steam Generated = 22,183,200 lbs

For CRE 15-3:

With heat exchanger valve closed:

October Energy Consumption Estimate = (2167.44 kWh) x (22,183,200 lbs / 25,786,500 lbs)
= 1864.57 kWh

With heat exchanger valve open:

October Energy Consumption Estimate = (4455.37 kWh) x (22,183,200 lbs / 25,786,500 lbs)
= 3832.79 kWh

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Case 2 continued:

For Worthington D-824:

With heat exchanger valve closed:

$$\text{October energy consumption estimate} = (2964.68\ kWh) \times \left(\frac{22{,}183{,}200\ lbs}{25{,}786{,}500\ lbs}\right)$$
$$= 2550.41\ kWh$$

With heat exchanger valve open:

$$\text{October energy consumption estimate} = (3933.29\ kWh) \times \left(\frac{22{,}183{,}200\ lbs}{25{,}786{,}500\ lbs}\right)$$
$$= 3383.67\ kWh$$

7) November 2012: Total steam Generated = 27, 051, 300 lbs

For CRE 15-3:

With heat exchanger valve closed

$$\text{November energy consumption estimate} = (2167.44\ kWh) \times \left(\frac{27{,}051{,}300\ lbs}{25{,}786{,}500\ lbs}\right)$$
$$= 2273.75\ kWh$$

With heat exchanger valve open

$$\text{November energy consumption estimate} = (4455.37\ kWh) \times \left(\frac{27{,}051{,}300\ lbs}{25{,}786{,}500\ lbs}\right)$$
$$= 4673.9\ kWh$$

For Worthington D-824:

With heat exchanger valve closed

$$\text{November energy consumption Estimate} = (2964.68\ kWh) \times \left(\frac{27{,}051{,}300\ lbs}{25{,}786{,}500\ lbs}\right)$$
$$= 3110.09\ kWh$$

With heat exchanger valve open

$$\text{November energy consumption Estimate} = (3933.29\ kwh) \times \left(\frac{27{,}051{,}300\ lbs}{25{,}786{,}500\ lbs}\right)$$
$$= 4126.21\ kWh$$

Case 2 Continued:

8) December 2012: Total Steam Generated = 34,752,700 lbs

For CRE 15-3:

With heat exchanger valve closed:

December energy consumption estimate $= (2167.44\ kWh) \times \left(\frac{34,752,700\ lbs}{25,786,500\ lbs}\right)$

$= 2921.08\ kWh$

With heat exchanger Valve open:

December energy consumption estimate $= (4455.37\ kWh) \times \left(\frac{34,752,700\ lbs}{25,786,500\ lbs}\right)$

$= 6004.54\ kWh$

For Worthington D-824:

With heat exchanger valve closed:

December energy consumption estimate $= (2964.68\ kWh) \times \left(\frac{34,752,700\ lbs}{25,786,500\ lbs}\right)$

$= 3995.53\ kWh$

With heat exchanger valve open:

December energy consumption estimate $= (3933.29\ kWh) \times \left(\frac{34,752,700\ lbs}{25,786,500\ lbs}\right)$

$= 5300.93\ kWh$

9) January 2013: Total Steam Generated = 37,793,500 lbs

For CRE 15-3:

With heat exchanger valve closed:

January energy consumption estimate $= (2167.44\ kWh) \times \left(\frac{37,793,500\ lbs}{25,786,500\ lbs}\right)$

$= 3176.67\ kWh$

With heat exchanger valve open:

January energy consumption estimate $= (4455.37\ kWh) \times \left(\frac{37,793,500\ lbs}{25,786,500\ lbs}\right)$

$= 6529.93\ kWh$

For Worthington D-824:

With heat exchanger Valve Closed:

January energy consumption estimate $= (2964.68) \times \left(\frac{37,793,500\ lbs}{25,786,500\ lbs}\right)$

$= 4345.13\ kWh$

Case 2 continued:

For Worthington D-824:

With heat exchanger valve open:

January energy consumption estimate $= (3933.29\ kWh) \times \left(\frac{37,793,500\ lbs}{25,786,500\ lbs}\right)$

$= 5764.75\ kWh$

10) February 2013: Total Steam Generated = 32,883,700 lbs

For CRE 15-3:

With heat exchanger valve closed:

February energy consumption estimate $= (2167.44\ kWh) \times \left(\frac{32,883,700\ lbs}{25,786,500\ lbs}\right)$

$= 2763.98\ kWh$

With heat exchanger valve open:

February energy consumption estimate $= (4455.37\ kWh) \times \left(\frac{32,883,700\ lbs}{25,786,500\ lbs}\right)$

$= 5681.62\ kWh$

For Worthington D-824:

With heat exchanger valve closed:

February energy consumption estimate $= (2964.68\ kWh) \times \left(\frac{32,883,700\ lbs}{25,786,500\ lbs}\right)$

$= 3780.65\ kWh$

With heat exchanger valve open:

February energy consumption estimate $= (3933.29\ kWh) \times \left(\frac{32,883,700\ lbs}{25,786,500\ lbs}\right)$

$= 5015.85\ kWh$

11) March 2013: Total steam Generated = 34,501,600 lbs

For CRE 15-3:

With heat exchanger valve closed:

March energy consumption estimate $= (2167.44\ kWh) \times \left(\frac{34,501,600\ lbs}{25,786,500\ lbs}\right)$

$= 2899.97\ kWh$

With heat exchanger valve open:

March energy consumption estimate $= (4455.37\ kWh) \times \left(\frac{34,501,600\ lbs}{25,786,500\ lbs}\right)$

$= 5961.16\ kWh$

Case 2 Continued; 11) March 2013:

For Worthington D-824:

With heat exchanger valve closed;

March energy consumption estimate $= (2964.68\ kWh) \times \left(\frac{34,501,600\ lbs}{25,786,500\ lbs}\right)$

$= 3966.66\ kWh$

With heat exchanger valve open:

March energy consumption estimate $= (3933.29\ kWh) \times \left(\frac{34,501,600\ lbs}{25,786,500\ lbs}\right)$

$= 5262.63\ kWh$

Based on the calculations shown above

With heat exchanger valve closed:

Estimated Annual energy consumption for CRE 15-3 = 24037.1 kWh

Estimated Annual energy consumption for Worthington D-824 = 32879.05 kWh

With heat exchanger valve open;

Estimated Annual energy consumption for CRE 15-3 = 49410.44 kWh

Estimated Annual energy consumption for Worthington D-824 = 43620.54 kWh

Appendix H.1: Case 2 – Method B – Energy Consumption Hand Calculations – Closed Heat Exchanger Valve

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Case 2: Method B - Calculations for times when heat exchanger valve was closed.

Whenever heat exchanger valve was closed, it is assumed that all water that the CRE 15-3 pumps and the Worthington D-824 pump flow to the deaerator tank is being turned into steam, since there is no recirculation of water. For this reason, at these situations one can divide the Average Power consumption of each pump by their respective average flowrate $\left(\frac{KW}{gpm}\right)$ and convert those units to $\frac{KJ}{lbm}$ in order to find for each pump how much energy it takes each pump to "produce" a pound of steam (approximate). Since we have the total amount of pounds of steam produced for a 12 month period, we would know the estimated Annual energy consumption each pump would have to produce that amount of steam. Again, this only works in situations we know the exact flow rate only going to the deaerator tank, since the assumption of all that water turning into steam is valid.

For CRE 15-3: $\frac{Avg.\ KW}{Avg.\ GPM}$

April 15: $\frac{Avg.\ KW}{Avg.\ GPM} = \frac{2.73756}{78.0811}$

April 16: $\frac{Avg.\ KW}{Avg.\ GPM} = \frac{3.09459}{86.1096}$

April 17: $\frac{Avg.\ KW}{Avg.\ GPM} = \frac{2.73733}{76.5625}$

April 18: $\frac{Avg\ KW}{Avg\ GPM} = \frac{3.47187}{95.6561}$

$$\text{Overall Average } \frac{KW}{GPM} = \frac{\frac{2.73756}{78.0811} + \frac{3.09459}{86.1096} + \frac{2.73733}{76.5625} + \frac{3.47187}{95.6561}}{4}$$

$$\text{Overall } \frac{Avg.\ KW}{Avg.\ GPM} = 0.035762\ \frac{KW}{GPM}$$

Converting $\frac{KW}{gal/min}$ to $\frac{KJ}{lbm\ (of\ water)}$; $KW = \frac{KJ}{s}$

$$0.035762\ \frac{KJ/s}{gal/min} \cdot \left(\frac{7.4805\ gal}{1\ ft^3}\right) \cdot \left(\frac{1\ ft^3}{62.43\ lbm}\right)\left(\frac{60\ sec}{1\ min}\right) = 0.257102\ \frac{KJ}{lbm}$$

∴ In case 2, while the heat exchanger valve is closed, the CRE15-3 estimate energy consumption was 0.257102 KJ for every pound of water it displaced.

Now on can find the total estimated Annual energy consumption for CRE 15-3 based on the amount of pounds of steam produced in the 12 month period used in Case 2.

Case 2: Heat exchanger valve closed Method B continued.

Based on the total Monthly steam production (lbs) provided in the tables in Appendix E:

Total Steam Produced by the power plant From May 2012 through April 2013

Total Steam (lbs) = 285,974,601 lbs

Find Estimated energy consumption for Annual Steam production:

CRE 15-3

$$\text{Energy consumption} = 285{,}974{,}601 \text{ lb} \times \left(0.257102 \frac{\text{KJ}}{\text{lb}}\right)$$

$$= 7.35247 \times 10^{7} \text{ KJ}$$

Convert KJ to kWh

$$\text{Energy consumption for CRE 15-3} = 7.35247 \times 10^{7} \text{ KJ} \cdot \left(\frac{1 \text{ hour}}{3600 \text{ Sec}}\right)$$

$$= 20{,}423.5 \text{ kWh}$$

Estimated energy consumption found using "Method A" (Power consumption And monthly estimates in Appendix H) = 24,037.1 kWh

Difference

$$\left(1 - \left(\frac{20{,}423.5 \text{ kWh}}{24{,}037.1 \text{ kWh}}\right)\right) \times 100\% = 15.03\% \text{ Difference between results}$$

For Worthington D-824: $\frac{\text{Avg. KW}}{\text{Avg. GPM}}$

April 15: $\frac{KW}{GPM} = \frac{4.02993}{69.1881}$

April 16: $\frac{KW}{GPM} = \frac{4.14426}{79.5078}$

April 17: $\frac{KW}{GPM} = \frac{4.00647}{70.734}$

April 18: $\frac{KW}{GPM} = \frac{4.29144}{86.1533}$

$$\text{Overall Average } \frac{KW}{GPM} = \frac{\frac{4.02993}{69.1881} + \frac{4.14426}{79.5078} + \frac{4.00647}{70.734} + \frac{4.29144}{86.1533}}{4}$$

$$\text{Overall Avg. } \frac{kW}{GPM} = 0.054206 \frac{KW}{GPM}$$

Converting $\frac{KJ/s}{gal/min}$ to $\frac{KJ}{\text{lbm (of water)}}$ $\qquad KW = KJ/s$

$$0.054206 \frac{KJ/s}{gal/min} \cdot \left(\frac{7.4805 \text{ gal}}{1 \text{ ft}^3}\right)\left(\frac{1 \text{ ft}^3}{62.43 \text{ lbm}}\right)\left(\frac{60 \text{ sec}}{1 \text{ min}}\right) = 0.389703 \frac{KJ}{lbm}$$

Case 2: Method B continued

Worthington D-824: 0.389703 $\frac{KJ}{lbm}$ (From calculations on the previous page)

Total pounds of steam produced by the Power Plant from May 2012 through April 2013 = 285,974,601 lbs

Estimated energy consumption for Annual steam Production

$$\text{Worthington D-824 Energy Consumption} = 285{,}974{,}601\,(lb) \times \left(0.389703\,\frac{KJ}{lb}\right)$$

$$= 1.11445 \times 10^{8}\ KJ$$

Convert KJ to KWh

$$\text{Energy consumption for Worthington D-824 (kWh)} = 1.11445 \times 10^{8}\ KJ \cdot \left(\frac{1\ hour}{3600 sec}\right)$$

$$= 30{,}957\ kWh$$

Estimated energy consumption found using "Method A" (in Power consumption and monthly estimates in Appendix H) = 32,879.05 kWh

Difference

$$\left(1 - \left(\frac{30{,}957\ kWh}{32{,}879.05\ kWh}\right)\right) \times 100\% = 5.85\%\ \text{difference between results}$$

Appendix I: Case 3 Energy Consumption Hand Calculations

Case 3: METhod A

a) Energy Consumption estimate calculations for the day in April 2013 with recorded power consumption data:

1) April 30th, 2013: Total Steam Generated = 621,600 lbs

For CRE 15-3:

Avg. Power Consumption = 0.80046 kW

Estimated Avg. Energy Consumption for April 30th = (0.80046 kW) x (24 hours)
= 19.211 kWh

For Worthington D-824:

Avg Power Consumption = 3.84249 kW

Estimated Avg. Energy consumption for April 30th = (3.84249 kW) x (24 hours)
= 92.2198 kWh

b) Energy consumption estimate calculations for the days in April 2013 without recorded power consumption data: Based on data gathered April 30th and Steam Generation ratios:

1) April 1st, 2013: Total Steam Generated = 1,004,400 lbs

For CRE 15-3:

$$\text{Estimated Avg. Energy Consumption} = (19.211\ kWh) \times \left(\frac{1{,}004{,}400\ lbs}{621{,}600\ lbs}\right) = 31.04171\ kWh$$

For Worthington D-824:

$$\text{Estimated Avg. Energy Consumption} = (92.2198\ kWh) \times \left(\frac{1{,}004{,}400\ lbs}{621{,}600\ lbs}\right) = 149.0115\ kWh$$

2) April 2, 2013: Total Steam Generated = 1,127,700 lbs

For CRE 15-3:

$$\text{Estimated Avg. Energy Consumption} = (19.211\ kWh) \times \left(\frac{1{,}127{,}700\ lbs}{621{,}600\ lbs}\right) = 34.85239\ kWh$$

For Worthington D-824:

$$\text{Estimated Avg Energy Consumption} = (92.2198\ kWh) \times \left(\frac{1{,}127{,}700\ lbs}{621{,}600\ lbs}\right) = 167.3042\ kWh$$

Case 3 Continued:

3) April 3, 2013: Total Steam Generated = 1,035,000 lbs

For CRE 15-3:

$$\text{Estimated Avg. Energy Consumption} = (19.211\ kWh) \times \left(\frac{1{,}035{,}000\ lbs}{621{,}600\ lbs}\right) = 31.98743\ kWh$$

For Worthington D-824:

$$\text{Estimated Avg. Energy Consumption} = (92.2198\ kWh) \times \left(\frac{1{,}035{,}000\ lbs}{621{,}600\ lbs}\right) = 153.5513\ kWh$$

4) April 4, 2013: Total Steam Generated = 929,500 lbs

For CRE 15-3:

$$\text{Estimated Avg. Energy Consumption} = (19.211\ kWh) \times \left(\frac{929{,}500\ lbs}{621{,}600\ lbs}\right) = 28.72687\ kWh$$

For Worthington D-824:

$$\text{Estimated Avg. Energy Consumption} = (92.2198\ kWh) \times \left(\frac{929{,}500\ lbs}{621{,}600\ lbs}\right) = 137.8995\ kWh$$

5) April 5, 2013: Total Steam Generated = 786,500 lbs

For CRE 15-3:

$$\text{Estimated Avg. Energy Consumption} = (19.211\ kWh) \times \left(\frac{786{,}500\ lbs}{621{,}600\ lbs}\right) = 24.30735\ kWh$$

For Worthington D-824

$$\text{Estimated Avg. Energy Consumption} = (92.2198\ kWh) \times \left(\frac{786{,}500\ lbs}{621{,}600\ lbs}\right) = 116.6842\ kWh$$

6) April 6, 2013: Total Steam Generated = 637,300 lbs

For CRE 15-3

$$\text{Estimated Avg. Energy Consumption} = (19.211\ kWh) \times \left(\frac{637{,}300\ lbs}{621{,}600\ lbs}\right) = 19.69622\ kWh$$

For Worthington D-824

$$\text{Estimated Avg Energy Consumption} = (92.2198\ kWh) \times \left(\frac{637{,}300\ lbs}{621{,}600\ lbs}\right) = 94.54903\ kWh$$

Case 3 Continued:

7) April 7th, 2013: Total Steam Generated = 631,700 lbs

For CRE 15-3:

Estimated Avg. Energy Consumption $= (19.211\,kWh) \times \left(\frac{631,700\ lbs}{621,600\ lbs}\right)$

$= 19.52315\ kWh$

For Worthington D-824:

Estimated Avg. Energy Consumption $= (92.2198\,kWh) \times \left(\frac{631,700\ lbs}{621,600\ lbs}\right)$

$= 93.71822\ kWh$

8) April 8, 2013: Total Steam Generated = 635,500 lbs

For CRE 15-3:

Estimated Avg Energy Consumption $= (19.211\,kWh) \times \left(\frac{635,500\ lbs}{621,600\ lbs}\right)$

$= 19.64059\ kWh$

For Worthington D-824:

Estimated Avg. Energy Consumption $= (92.2198\,kWh) \times \left(\frac{635,500\ lbs}{621,600\ lbs}\right)$

$= 94.28199\ kWh$

9) April 9, 2013: Total Steam Generated = 667,400 lbs

For CRE 15-3:

Estimated Avg. Energy Consumption $= (19.211\,kWh) \times \left(\frac{667,400\ lbs}{621,600\ lbs}\right)$

$= 20.62648\ kWh$

For Worthington D-824:

Estimated Avg. Energy Consumption $= (92.2198\,kWh) \times \left(\frac{667,400\ lbs}{621,600\ lbs}\right)$

$= 99.01463\ kWh$

10) April 10, 2013: Total Steam Generated = 991,600 lbs

For CRE 15-3

Estimated Avg Energy Consumption $= (19.211\,kWh) \times \left(\frac{991,600\ lbs}{621,600\ lbs}\right)$

$= 30.64612\ kWh$

For Worthington D-824

Estimated Avg. Energy Consumption $= (92.2198\,kWh) \times \left(\frac{991,600\ lbs}{621,600\ lbs}\right)$

$= 147.1125\ kWh$

11) April 11, 2013: Total Steam Generated = 1,086,000 lbs

For CRE 15-3:

Estimated Avg Energy Consumption $= (19.211\,kWh) \times \left(\frac{1,086,000\ lbs}{621,600\ lbs}\right)$

$= 33.56362\ kWh$

Case 3 Continued: April 11, 2013

For Worthington D-824:

Estimated Avg. Energy Consumption $= (92.2198\,kWh) \times \left(\frac{1{,}086{,}000\ lbs}{621{,}600\ lbs}\right)$

$= 161.1176\ kWh$

12) April 12th, 2013: Total Steam Generated = 1,016,800 lbs

For CRE 15-3:

Estimated Avg. Energy Consumption $= (19.211\,kWh) \times \left(\frac{1{,}016{,}800\ lbs}{621{,}600\ lbs}\right)$

$= 31.42494\ kWh$

For Worthington D-824:

Estimated Avg. Energy Consumption $= (92.2198\,kWh) \times \left(\frac{1{,}016{,}800\ lbs}{621{,}600\ lbs}\right)$

$= 150.8512\ kWh$

13) April 13th, 2013: Total Steam Generated = 815,400 lbs

For CRE 15-3:

Estimated Avg. Energy Consumption $= (19.211\,kWh) \left(\frac{815{,}400\ lbs}{621{,}600\ lbs}\right)$

$= 25.20053\ kWh$

For Worthington D-824:

Estimated Avg. Energy Consumption $= (92.2198\,kWh) \left(\frac{815{,}400\ lbs}{621{,}600\ lbs}\right)$

$= 120.9717\ kWh$

14) April 14, 2013: Total Steam Generated = 643,900 lbs

For CRE 15-3:

Estimated Avg Energy Consumption $= (19.211\,kWh) \times \left(\frac{643{,}900\ lbs}{621{,}600\ lbs}\right)$

$= 19.9002\ kWh$

For Worthington D-824:

Estimated Avg. Energy Consumption $= (92.2198\,kWh) \times \left(\frac{643{,}900\ lbs}{621{,}600\ lbs}\right)$

$= 95.5282\ kWh$

15) April 15, 2013: Total Steam Generated = 889,400 lbs

For CRE 15-3:

Estimated Avg. Energy Consumption $= (19.211\,kWh) \times \left(\frac{889{,}400\ lbs}{621{,}600\ lbs}\right)$

$= 27.48755\ kWh$

For Worthington D-824:

Estimated Avg. Energy Consumption $= (92.2198\,kWh) \times \left(\frac{889{,}400\ lbs}{621{,}600\ lbs}\right)$

$= 131.9503\ kWh$

Case 3 continued

16) April 16, 2013: Total Steam Generated = 980,700 lbs

For CRE 15-3:

Estimated Avg. Energy Consumption = $(19.211\ kWh) \times \left(\frac{980{,}700\ lbs}{621{,}600\ lbs}\right)$

$= 30.30925\ kWh$

For Worthington D-824:

Estimated Avg. Energy Consumption = $(92.2198\ kWh) \times \left(\frac{980{,}700\ lbs}{621{,}600\ lbs}\right)$

$= 145.4954\ kWh$

17) April 17, 2013: Total Steam Generated = 900,200 lbs

For CRE 15-3:

Estimated Avg. Energy Consumption = $(19.211\ kWh) \times \left(\frac{900{,}200\ lbs}{621{,}600\ lbs}\right)$

$= 27.82134\ kWh$

For Worthington D-824:

Estimated Avg. Energy Consumption = $(92.2198\ kWh) \times \left(\frac{900{,}200\ lbs}{621{,}600\ lbs}\right)$

$= 133.5525\ kWh$

18) April 18, 2013: Total Steam Generated = 1,046,700 lbs

For CRE 15-3:

Estimated Avg. Energy Consumption = $(19.211\ kWh) \times \left(\frac{1{,}046{,}700\ lbs}{621{,}600\ lbs}\right)$

$= 32.34902\ kWh$

For Worthington D-824:

Estimated Avg. Energy Consumption = $(92.2198\ kWh) \times \left(\frac{1{,}046{,}700\ lbs}{621{,}600\ lbs}\right)$

$= 155.2871\ kWh$

19) April 19, 2013: Total Steam Generated = 978,900 lbs

For CRE 15-3:

Estimated Avg. Energy Consumption = $(19.211\ kWh) \times \left(\frac{978{,}900\ lbs}{621{,}600\ lbs}\right)$

$= 30.25362\ kWh$

For Worthington D-824:

Estimated Avg. Energy Consumption = $(92.2198\ kWh) \times \left(\frac{978{,}900\ lbs}{621{,}600\ lbs}\right)$

$= 145.2284\ kWh$

20) April 20, 2013: Total Steam Generated = 916,700 lbs

For CRE 15-3:

Estimated Avg. Energy Consumption = $(19.211\ kWh) \times \left(\frac{916{,}700\ lbs}{621{,}600\ lbs}\right)$

$= 28.33128\ kWh$

For Worthington D-824:

Estimated Avg. Energy Consumption = $(92.2198\ kWh) \times \left(\frac{916{,}700\ lbs}{621{,}600\ lbs}\right)$

$= 136.0005\ kWh$

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(Case 3 continued)

21) April 21st, 2013: Total Steam Generated = 743,600 lbs

For CRE 15-3:

Estimated Avg. Energy Consumption = $(19.211 \text{ kWh}) \times \left(\frac{743{,}600 \text{ lbs}}{621{,}600 \text{ lbs}}\right)$

$= 22.9815 \text{ kWh}$

For Worthington D-824:

Estimated Avg. Energy Consumption = $(92.2198 \text{ kWh}) \times \left(\frac{743{,}600 \text{ lbs}}{621{,}600 \text{ lbs}}\right)$

$= 110.3196 \text{ kWh}$

22) April 22, 2013: Total Steam Generated = 811,300 lbs

For CRE 15-3:

Estimated Avg. Energy Consumption = $(19.211 \text{ kWh}) \times \left(\frac{811{,}300 \text{ lbs}}{621{,}600 \text{ lbs}}\right)$

$= 25.07382 \text{ kWh}$

For Worthington D-824:

Estimated Avg. Energy Consumption = $(92.2198 \text{ kWh}) \times \left(\frac{811{,}300 \text{ lbs}}{621{,}600 \text{ lbs}}\right)$

$= 120.3635 \text{ kWh}$

23) April 23, 2013: Total Steam Generated = 1,136,400 lbs

For CRE 15-3:

Estimated Avg. Energy Consumption = $(19.211 \text{ kWh}) \times \left(\frac{1{,}136{,}400 \text{ lbs}}{621{,}600 \text{ lbs}}\right)$

$= 35.12127 \text{ kWh}$

For Worthington D-824:

Estimated Avg. Energy Consumption = $(92.2198 \text{ kWh}) \times \left(\frac{1{,}136{,}400 \text{ lbs}}{621{,}600 \text{ lbs}}\right)$

$= 168.5949 \text{ kWh}$

24) April 24, 2013: Total Steam Generated = 1,041,200 lbs

For CRE 15-3:

Estimated Avg. Energy Consumption = $(19.211 \text{ kWh}) \times \left(\frac{1{,}041{,}200 \text{ lbs}}{621{,}600 \text{ lbs}}\right)$

$= 32.17904 \text{ kWh}$

For Worthington D-824:

Estimated Avg. Energy Consumption = $(92.2198 \text{ kWh}) \times \left(\frac{1{,}041{,}200 \text{ lbs}}{621{,}600 \text{ lbs}}\right)$

$= 154.4711 \text{ kWh}$

25) April 25, 2013: Total Steam Generated = 649,000 lbs

For CRE 15-3:

Estimated Avg. Energy Consumption = $(19.211 \text{ kWh}) \times \left(\frac{649{,}000 \text{ lbs}}{621{,}600 \text{ lbs}}\right)$

$= 20.05782 \text{ kWh}$

For Worthington D-824:

Estimated Avg. Energy Consumption = $(92.2198 \text{ kWh}) \times \left(\frac{649{,}000 \text{ lbs}}{621{,}600 \text{ lbs}}\right)$

$= 96.28483 \text{ kWh}$

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Case 3 continued:

26) April 26th, 2013: Total Steam Generated = 879,900 lbs

For CRE 15-3:

Estimated Avg. Energy Consumption = (19.211 KWh) x (879,900 lbs / 621,600 lbs)

= 27.19395 KWh

For Worthington D-824:

Estimated Avg. Energy Consumption = (92.2198 KWh) x (879,900 lbs / 621,600 lbs)

= 130.5409 KWh

27) April 27, 2013: Total steam Generated = 830,600 lbs

For CRE 15-3:

Estimated Avg. Energy consumption = (19.211 KWh) x (830,600 lbs / 621,600 lbs)

= 25.6703 KWh

For Worthington D-824:

Estimated Avg. Energy Consumption = (92.2198 KWh) x (830,600 lbs / 621,600 lbs)

= 123.2268 KWh

28) April 28, 2013: Total Steam Generated = 714,900 lbs

For CRE 15-3:

Estimated Avg. Energy consumption = (19.211 KWh) x (714,900 lbs / 621,600 lbs)

= 22.0945 KWh

For Worthington D-824:

Estimated Avg. Energy consumption = (92.2198 KWh) x (714,900 lbs / 621,600 lbs)

= 106.0617 KWh

29) April 29, 2013: Total Steam Generated = 636,700 lbs

For CRE 15-3:

Estimated Avg. Energy consumption = (19.211 KWh) x (636,700 lbs / 621,600 lbs)

= 19.67768 KWh

For Worthington D-824:

Estimated Avg. Energy consumption = (92.2198 KWh) x (636,700 lbs / 621,600 lbs)

= 94.46002 KWh

Based on the Calculations Above:

April's estimated energy consumption:

For CRE 15-3 = 796.9505 KWh

For Worthington D-824 = 3825.653 KWh

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Case 3 Continued:

C) Energy Consumption estimate Calculations for months without recorded power consumption data: Based on the estimates found for April 2013 and steam Generation ratios.

1) May 2012: Total Steam Generated = 13,620,200 lbs

For CRE 15-3:

$$\text{Estimated Energy Consumption} = (796.9505\ \text{kWh}) \times \left(\frac{13,620,200\ \text{lbs}}{25,786,500\ \text{lbs}}\right) = 415.66\ \text{kWh}$$

For Worthington D-824:

$$\text{Estimated Energy consumption} = (3825.653\ \text{kWh}) \times \left(\frac{13,620,200\ \text{lbs}}{25,786,500\ \text{lbs}}\right) = 2020.68\ \text{kWh}$$

2) June 2012: Total Steam Generated = 14,020,700 lbs

For CRE 15-3:

$$\text{Estimated Energy consumption} = (796.9505\ \text{kWh}) \times \left(\frac{14,020,700\ \text{lbs}}{25,786,500\ \text{lbs}}\right) = 427.883\ \text{kWh}$$

For Worthington D-824:

$$\text{Estimated Energy Consumption} = (3825.653\ \text{kWh}) \times \left(\frac{14,020,700\ \text{lbs}}{25,786,500\ \text{lbs}}\right) = 2080.09\ \text{kWh}$$

3) July 2012: Total steam Generated = 12,954,101 lbs.

For CRE 15-3:

$$\text{Estimated Energy consumption} = (796.9505\ \text{kWh}) \times \left(\frac{12,954,101\ \text{lbs}}{25,786,500\ \text{lbs}}\right) = 400.356\ \text{kWh}$$

For Worthington D-824:

$$\text{Estimated Energy Consumption} = (3825.653\ \text{kWh}) \times \left(\frac{12,954,101\ \text{lbs}}{25,786,500\ \text{lbs}}\right) = 1921.85\ \text{kWh}$$

Case3 continued:

4) August 2012: Total Steam Generated = 14,783,000 lbs

For CRE 15-3:

$$\text{Estimated Energy consumption} = (796.9505\ \text{kWh}) \times \left(\frac{14{,}783{,}000\ \text{lbs}}{25{,}786{,}500\ \text{lbs}}\right)$$

$$= 456.879\ \text{kWh}$$

For Worthington D-824:

$$\text{Estimated Energy Consumption} = (3825.653\ \text{kWh}) \times \left(\frac{14{,}783{,}000\ \text{lbs}}{25{,}786{,}500\ \text{lbs}}\right)$$

$$= 2193.19\ \text{kWh}$$

5) September 2012: Total steam Generated = 15,644,100 lbs

For CRE 15-3:

$$\text{Estimated Energy Consumption} = (796.9505\ \text{kWh}) \times \left(\frac{15{,}644{,}100\ \text{lbs}}{25{,}786{,}500\ \text{lbs}}\right)$$

$$= 483.492\ \text{kWh}$$

For Worthington D-824:

$$\text{Estimated Energy Consumption} = (3825.653\ \text{kWh}) \times \left(\frac{15{,}644{,}100\ \text{lbs}}{25{,}786{,}500\ \text{lbs}}\right)$$

$$= 2320.94\ \text{kWh}$$

6) October 2012: Total Steam Generated = 22,183,200 lbs

For CRE 15-3:

$$\text{Estimated Energy Consumption} = (796.9505\ \text{kWh}) \times \left(\frac{22{,}183{,}200\ \text{lbs}}{25{,}786{,}500\ \text{lbs}}\right)$$

$$= 685.588\ \text{kWh}$$

For Worthington D-824:

$$\text{Estimated Energy Consumption} = (3825.653\ \text{kWh}) \times \left(\frac{22{,}183{,}200\ \text{lbs}}{25{,}786{,}500\ \text{lbs}}\right)$$

$$= 3291.07\ \text{kWh}$$

7) November 2012: Total Steam Generated = 27,051,300 lbs

For CRE 15-3:

$$\text{Estimated Energy consumption} = (796.9505\ \text{kWh}) \times \left(\frac{27{,}051{,}300\ \text{lbs}}{25{,}786{,}500\ \text{lbs}}\right)$$

$$= 836.04\ \text{kWh}$$

For Worthington D-824:

$$\text{Estimated Energy Consumption} = (3825.653\ \text{kWh}) \times \left(\frac{27{,}051{,}300\ \text{lbs}}{25{,}786{,}500\ \text{lbs}}\right)$$

$$= 4013.3\ \text{kWh}$$

Case 3 Continued:

8) December 2012: Total steam Generated = 34,752,700 lbs

For CRE 15-3:

$$\text{Estimated Energy Consumption} = (796.9505\ kWh) \times \left(\frac{34,752,700\ lbs}{25,786,500\ lbs}\right)$$

$$= 1074.06\ kWh$$

For Worthington D-824:

$$\text{Estimated Energy consumption} = (3825.653\ kWh) \times \left(\frac{34,752,700\ lbs}{25,786,500\ lbs}\right)$$

$$= 5155.87\ kWh$$

9) January 2013: Total Steam Generated = 37,793,500 lbs

For CRE 15-3:

$$\text{Estimated Energy consumption} = (796.9505\ kWh) \times \left(\frac{37,793,500\ lbs}{25,786,500\ lbs}\right)$$

$$= 1168.04\ kWh$$

For Worthington D-824:

$$\text{Estimated Energy Consumption} = (3825.653\ kWh) \times \left(\frac{37,793,500\ lbs}{25,786,500\ lbs}\right)$$

$$= 5607\ kWh$$

10) February 2013: Total Steam Generated = 32,883,700 lbs

For CRE 15-3:

$$\text{Estimated Energy Consumption} = (796.9505\ kWh) \times \left(\frac{32,883,700\ lbs}{25,786,500\ lbs}\right)$$

$$= 1016.29\ kWh$$

For Worthington D-824:

$$\text{Estimated Energy Consumption} = (3825.653\ kWh) \times \left(\frac{32,883,700\ lbs}{25,786,500\ lbs}\right)$$

$$= 4878.58\ kWh$$

11) March 2013: Total Steam Generated = 34,501,600 lbs

For CRE 15-3:

$$\text{Estimate Energy Consumption} = (796.9505\ kWh) \times \left(\frac{34,501,600\ lbs}{25,786,500\ lbs}\right)$$

$$= 1066.3\ kWh$$

For Worthington D-824:

$$\text{Estimated Energy Consumption} = (3825.653\ kWh) \times \left(\frac{34,501,600\ lbs}{25,786,500\ lbs}\right)$$

$$= 5118.61\ kWh$$

Case 3 (continued)

Based on the estimates calculated for each Month, the estimated Annual energy consumption for each pump is shown below:

For CRE 15-3:

Annual Estimated Energy Consumption = 8827.5385 kWh

For Worthington D-824:

Annual Estimated Energy Consumption = 42426.833 kWh

Appendix I.1: Case 3 – Method B – Energy Consumption Hand Calculations

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Case 3: Method B

Follows same procedures and assumptions from Case2 - MethodB in Appendix H.1.

For CRE 15-3: Data From April 30, 2013

Avg. Power consumption (April 30) = 0.800457 KW

Avg. Flow rate (April 30) = 56.07967 GPM

$\frac{KW}{GPM} = \frac{0.800457\,KW}{56.07967\,GPM} = 0.014274\,\frac{KW}{GPM}$ (Convert to $\frac{KJ}{lb_m}$)

$0.014274\,\frac{KJ/s}{gal/min} \cdot \left(\frac{7.4805\,gal}{1\,ft^3}\right) \cdot \left(\frac{1\,ft^3}{62.43\,lb_m}\right)\left(\frac{60s}{1\,min}\right) = 0.102617\,\frac{KJ}{lbm}$

Total steam Produced by Power Plant From May 2012 to April 2013:

Total steam (lb) = 285,974,601 lb

CRE 15-3
Estimated Annual Energy Consumption = $(285{,}974{,}601\,lb) \times \left(0.102617\,\frac{KJ}{lb_m}\right)$
$= 2.9346 \times 10^7\,KJ$

Convert to KWh

Estimated Annual Energy Consumption for CRE 15-3 = $2.9346 \times 10^7\,KJ \cdot \left(\frac{1\,hr}{3600\,sec}\right)$
$= 8151.66\,KWh$

Estimated Annual energy consumption found using "Method A" (in Appendix I)

Difference 8827.54 KWh

$\left(1 - \left(\frac{8151.66\,KWh}{8827.54\,KWh}\right)\right) \times 100\% = 7.66\%$ difference between results.

For Worthington D-824: Data from April 30, 2013

Average Power Consumption (KW) = 3.842486 KW

Average Flow rate (GPM) = 56.70446 GPM

$\frac{KW}{GPM} = \frac{3.842486\,KW}{56.70446\,GPM} = 0.067763\,\frac{KW}{GPM}$ (Convert to $\frac{KJ}{lbm}$)

$0.067763\,\frac{KJ/s}{gal/min} \cdot \left(\frac{7.4805\,gal}{1\,ft^3}\right)\left(\frac{1\,ft^3}{62.43\,lb_m}\right)\left(\frac{60s}{1\,min}\right) = 0.487173\,\frac{KJ}{lb_m}$

Case 3: Method B continued

Total Steam produced From May 2012 through April 2013 = 285,974,601 lb

Worthington D-824

Estimated Annual Energy Consumption = $(285,974,601\ \text{lb}) \cdot \left(0.487173\ \frac{\text{KJ}}{\text{lb}}\right)$

$= 1.39319 \times 10^{8}\ \text{KJ}$

Convert to KWh

Estimated Annual Energy Consumption For Worthington D-824 = $1.39319 \times 10^{8}\ \text{KJ} \cdot \left(\frac{1\text{hr}}{3600\text{s}}\right)$

$= 38699.8\ \text{KWh}$

Estimated Annual Energy Consumption found using "MethodA" (in Appendix I)

42426.833 KWh

Difference

$\left(1 - \left(\frac{38699.8\text{KWh}}{42426.833\text{KWh}}\right)\right) \times 100\%$ = 8.78% difference betwee Results

Appendix J: Case 4 Energy Consumption Hand Calculations

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Case 4:

a) Energy consumption estimate calculations for month (March) with recorded power consumption Data:

1) March 2013: Total Steam Generated = 34,501,600 lbs

For CRE 15-3: (Not Providing water to heat exchanger Due to low discharge P.

Avg. Power Consumption = 1.70051 KW (Base on data from March 12, 14, 18, 19, 20, 21 and 26)

Avg. Month Energy Consumption (kWh) = (1.70051 kW) x (744 hours)
= 1265.18 kWh

For Worthington D-824: Providing water to heat exchanger

Avg. Power consumption = 5.487127 kW

Avg. Month Energy Consumption (kWh) = (5.487127 kW) x (744 hours)
= 4082.42 kWh

Based on the data from Case 2, when the heat exchanger access valve was closed with the Worthington D-824 pump in operation, its power consumption had an average drop of approximately 1.34488 kW. Considering: the fact that the CRE 15-3 did not provided water to the heat exchanger due to its low discharge pressure when running in level control mode, while the worthington did provide water to the heat exchanger, this average drop will be used to better estimate the energy consumption difference between the 2 pumps. Because by using such power consumption drop for the Worthington D-824 pump, one is assuming that would represent the power necessary to provide water only to the deaerator tank, just like the CRE15-3.

For Worthington D-824: Not providing water to heat exchanger

Avg. Power Consumption = (5.487127 kW) - (1.34488 kW)
= 4.14225 kW

Avg. Month Energy consumption (kWh) = (4.14225 kW) x (744 hours)
= 3081.83 kWh

Case 4 continued:

b) Energy Consumption estimate calculations for Months Without recorded power consumption data. Based on Steam Generation Ratios:

1) April 2012: Total steam Generated = 18,715,700 lbs

For CRE 15-3:

$$\text{Estimated energy consumption} = (1265.18\ kWh) \times \left(\frac{18,715,700\ lbs}{34,501,600\ lbs}\right)$$

$$= 686.308\ kWh$$

For Worthington D-824:

Considering heat exchanger:

$$\text{Estimated energy consumption} = (4082.42\ kWh) \times \left(\frac{18,715,700\ lbs}{34,501,600\ lbs}\right)$$

$$= 2214.55\ kWh$$

Not considering heat exchanger:

$$\text{Estimated energy consumption} = (3081.83\ kWh) \times \left(\frac{18,715,700\ lbs}{34,501,600\ lbs}\right)$$

$$= 1671.77\ kWh$$

2) May 2012: Total steam Generated = 13,620,200 lbs

For CRE 15-3:

$$\text{Estimated energy consumption} = (1265.18\ kWh) \times \left(\frac{13,620,200\ lbs}{34,501,600\ lbs}\right)$$

$$= 499.455\ kWh$$

For Worthington D-824:

Considering heat exchanger:

$$\text{Estimated energy consumption} = (4082.42\ kWh) \times \left(\frac{13,620,200\ lbs}{34,501,600\ lbs}\right)$$

$$= 1611.62\ kWh$$

Not considering heat exchanger:

$$\text{Estimated energy consumption} = (3081.83\ kWh) \times \left(\frac{13,620,200\ lbs}{34,501,600\ lbs}\right)$$

$$= 1216.61\ kWh$$

3) June 2012: Total Steam Generated = 14,020,700 lbs

For CRE 15-3:

$$\text{Estimated energy consumption} = (1265.18\ kWh) \times \left(\frac{14,020,700\ lbs}{34,501,600\ lbs}\right)$$

$$= 514.142\ kWh$$

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Case 4 continued: June 2012

For Worthington D-824:

Considering Heat exchanger

$$\text{Estimated Energy Consumption} = (4082.42\ kWh) \times \left(\frac{14{,}020{,}700\ lbs}{34{,}501{,}600\ lbs}\right) = 1659.01\ kWh$$

Not considering Heat exchanger:

$$\text{Estimated energy consumption} = (3081.83\ kWh) \times \left(\frac{14{,}020{,}700\ lbs}{34{,}501{,}600\ lbs}\right) = 1252.39\ kWh$$

4) July 2012: Total Steam Generated = 12,954,101 lbs

For CRE 15-3:

$$\text{Estimated energy consumption} = (1265.18\ kWh) \times \left(\frac{12{,}954{,}101\ lbs}{34{,}501{,}600\ lbs}\right) = 475.029\ kWh$$

For Worthington D-824:

Considering Heat exchanger:

$$\text{Estimated energy consumption} = (4082.42\ kWh) \times \left(\frac{12{,}954{,}101\ lbs}{34{,}501{,}600\ lbs}\right) = 1532.8\ kWh$$

Not considering Heat exchanger:

$$\text{Estimated energy consumption} = (3081.83\ kWh) \times \left(\frac{12{,}954{,}101\ lbs}{34{,}501{,}600\ lbs}\right) = 1157.12\ kWh$$

5) August 2012: Total Steam generated = 14,783,000 lbs

For CRE 15-3:

$$\text{Estimated energy consumption} = (1265.18\ kWh) \times \left(\frac{14{,}783{,}000\ lbs}{34{,}501{,}600\ lbs}\right) = 542.095\ kWh$$

For Worthington D-824:

Considering heat exchanger:

$$\text{Estimated energy consumption} = (4082.42\ kWh) \times \left(\frac{14{,}783{,}000\ lbs}{34{,}501{,}600\ lbs}\right) = 1749.21\ kWh$$

Not considering Heat exchanger:

$$\text{Estimated energy consumption} = (3081.83\ kWh) \times \left(\frac{14{,}783{,}000\ lbs}{34{,}501{,}600\ lbs}\right) = 1320.48\ kWh$$

Case 4 continued:

6) September 2012: Total Steam Generated = 15,644,100 lbs

For CRE 15-3:

Estimated Energy Consumption = $(1265.18\,kWh) \times \left(\frac{15,644,100\ lbs}{34,501,600\ lbs}\right)$

$= 573.672\,kWh$

For Worthington D-824:

Considering Heat exchanger:

Estimated energy consumption = $(4082.42\,kWh) \times \left(\frac{15,644,100\ lbs}{34,501,600\ lbs}\right)$

$= 1851.1\,kWh$

Not Considering Heat exchanger:

Estimated energy consumption = $(3081.83\,kWh) \times \left(\frac{15,644,100\ lbs}{34,501,600\ lbs}\right)$

$= 1397.4\,kWh$

7) October 2012: Total Steam Generated = 22,183,200 lbs

For CRE 15-3:

Estimated energy consumption = $(1265.18\,kWh) \times \left(\frac{22,183,200\ lbs}{34,501,600\ lbs}\right)$

$= 813.462\,kWh$

For Worthington D-824:

Considering Heat exchanger:

Estimated energy consumption = $(4082.42\,kWh) \times \left(\frac{22,183,200\ lbs}{34,501,600\ lbs}\right)$

$= 2624.84\,kWh$

Not considering Heat exchanger

Estimated energy consumption = $(3081.83\,kWh) \times \left(\frac{22,183,200\ lbs}{34,501,600\ lbs}\right)$

$= 1981.5\,kWh$

8) November 2012: Total Steam Generated = 27,051,300 lbs

For CRE 15-3:

Estimated energy consumption = $(1265.18\,kWh) \times \left(\frac{27,051,300\ lbs}{34,501,600\ lbs}\right)$

$= 991.976\,kWh$

For Worthington D-824:

Considering heat exchanger:

Estimated energy consumption = $(4082.42\,kWh) \times \left(\frac{27,051,300\ lbs}{34,501,600\ lbs}\right)$

$= 3200.86\,kWh$

Not considering heat exchanger:

Estimated energy consumption = $(3081.83\,kWh) \times \left(\frac{27,051,300\ lbs}{34,501,600\ lbs}\right)$

$= 2416.34\,kWh$

Case 4 continued:

9) December 2012: Total Steam Generated = 34,752,700 lbs

For CRE 15-3

Estimated energy consumption = (1265.18 kWh) x (34,752,700 lbs / 34,501,600 lbs)

= 1274.39 kWh

For Worthington D-824:

Considering Heat exchanger:

Estimated energy consumption = (4082.42 kWh) x (34,752,700 lbs / 34,501,600 lbs)

= 4112.13 kWh

Not considering Heat Exchanger

Estimated energy consumption = (3081.83 kWh) x (34,752,700 lbs / 34,501,600 lbs)

= 3104.26 kWh

10) January 2013: Total Steam Generated = 37,793,500 lbs

For CRE 15-3:

Estimated energy consumption = (1265.18 kWh) x (37,793,500 lbs / 34,501,600 lbs)

= 1385.89 kWh

For Worthington D-824:

Considering Heat exchanger:

Estimated energy consumption = (4082.42 kWh) x (37,793,500 lbs / 34,501,600 lbs)

= 4471.94 kWh

Not considering Heat exchanger:

Estimated energy consumption = (3081.83 kWh) x (37,793,500 lbs / 34,501,600 lbs)

= 3375.88 kWh

11) February 2013: Total Steam Generated = 32,883,700 lbs

For CRE 15-3:

Estimated energy consumption = (1265.18 kWh) x (32,883,700 lbs / 34,501,600 lbs)

= 1205.85 kWh

For Worthington D-824:

Considering Heat exchanger:

Estimated energy consumption = (4082.42 kWh) x (32,883,700 lbs / 34,501,600 lbs)

= 3890.98 kWh

Not considering heat exchanger:

Estimated energy consumption = (3081.83 kWh) x (32,883,700 lbs / 34,501,600 lbs)

= 2937.31 kWh

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Case 4 Continued:

Based on the estimates for each month, the annual energy consumptions for this case are shown below:

For CRE 15-3:

Estimated Annual Energy Consumption = 10227.45 kWh

For Worthington D-824:

Considering Heat exchanger:

Estimated Annual Energy Consumption = 33001.46 kWh

Not considering Heat exchanger:

Estimated Annual Energy Consumption = 24912.89 kWh

Appendix K: Case 1 Detailed Life Cycle Cost Report [23]

NIST BLCC 5.3-12: Detailed LCC Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

General Information	
Analysis Type:	FEMP Analysis, Energy Project
Project Name:	Variable Speed Pump vs. Constant Speed Pump
Project Location:	Kansas
Analyst:	Fabian Philip Schmidt
Base Date:	1-Apr-12
Service Date:	1-Apr-12
Study Period:	20 years 0 months (April 1, 2012 through March 31, 2032)
Discount Rate:	3.50%
Discounting Convention:	End-of-Year

Discount and Escalation Rates are NOMINAL (inclusive of general inflation)

Case 1

Base Case - Worthington D-824 Constant Speed Pump

Initial Cost Data (not Discounted)

Initial Capital Costs

(adjusted for price escalation)	
Initial Capital Costs for All Components:	$6,500

Component: Initial Costs

Cost-Phasing

Date	Portion	Yearly Cost
1-Apr-12	100%	$6,500
	------------	------------
Total (for Component)		$6,500

Energy Costs: Electricity	

(base-year dollars)

Average Annual Usage	Price/Unit	Average Annual Cost	Average Annual Demand	Average Annual Rebate
53,394.6 kWh	$0.079	$4,218	$480	$0

Water Costs: Make up Water Cost	

(base-year dollars)

	Average Annual Usage		
Water	Units/Year	Price/Unit	Average Annual Cost
@ Summer Rates	1,696,280.0 Gal	$0.00287	$4,868
@ Winter Rates	3,659,400.0 Gal	$0.00287	$10,502

Life-Cycle Cost Analysis		
	Present Value	Annual Value
Initial Capital Costs	$6,500	$457

Energy Costs	Present Value	Annual Value
Energy Consumption Costs	$65,181	$4,587
Energy Demand Charges	$7,417	$522
Energy Utility Rebates	$0	$0
	------------	------------
Subtotal (for Energy):	$72,599	$5,109

Water Usage Costs	$229,021	$16,116
Water Disposal Costs	$0	$0

Operating, Maintenance & Repair Costs		
Component: Initial Costs	Present Value	Annual Value
Annually Recurring Costs	$20,000	$1,407
Non-Annually Recurring Costs	$2,000	$141
	------------	------------
Subtotal (for OM&R):	$22,000	$1,548

Replacements to Capital Components	Present Value	Annual Value
Component: Initial Costs	$2,000	$141
	------------	------------
Subtotal (for Replacements):	$2,000	$141

Residual Value of Original Capital Components	Present Value	Annual Value
Component: Initial Costs	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

Residual Value of Capital Replacements	Present Value	Annual Value
Component: Initial Costs	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

	Present Value	Annual Value
Total Life-Cycle Cost	$332,119	$23,370

Alternative: Grundfos CRE 15-3 Variable Speed Pump

Initial Cost Data (not Discounted)

Initial Capital Costs

(adjusted for price escalation)

Initial Capital Costs for All Components:	$15,000

Component:

Cost-Phasing

Date	Portion	Yearly Cost
1-Apr-12	100%	$15,000
	------------	------------
Total (for Component)		$15,000

Energy Costs: Electricity

(base-year dollars)

Average Annual Usage	Price/Unit	Average Annual Cost	Average Annual Demand	Average Annual Rebate
53,621.5 kWh	$0.08	$4,236	$480	$0

Water Costs: Make up Water Cost

(base-year dollars)

	Average Annual Usage		
Water	Units/Year	Price/Unit	Average Annual Cost
@ Summer Rates	1,696,280.0 Gal	$0.00287	$4,868
@ Winter Rates	3,659,400.0 Gal	$0.00287	$10,502

Life-Cycle Cost Analysis		
	Present Value	Annual Value
Initial Capital Costs	$15,000	$1,056

Energy Costs	Present Value	Annual Value
Energy Consumption Costs	$65,458	$4,606
Energy Demand Charges	$7,417	$522
Energy Utility Rebates	$0	$0
	------------	------------
Subtotal (for Energy):	$72,876	$5,128

Water Usage Costs	$229,021	$16,116
Water Disposal Costs	$0	$0

Operating, Maintenance & Repair Costs		
Component:	Present Value	Annual Value
Annually Recurring Costs	$20,000	$1,407
Non-Annually Recurring Costs	$4,000	$281
	------------	------------
Subtotal (for OM&R):	$24,000	$1,689

Replacements to Capital Components	Present Value	Annual Value
Component:	$2,000	$141
	------------	------------
Subtotal (for Replacements):	$2,000	$141

Residual Value of Original Capital Components	Present Value	Annual Value
Component:	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

Residual Value of Capital Replacements	Present Value	Annual Value
Component:	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

	Present Value	Annual Value
Total Life-Cycle Cost	$342,896	$24,129

Appendix L: Case 2 with Heat Exchanger Valve Open, Detailed Life Cycle Cost Report [23]

NIST BLCC 5.3-12: Detailed LCC Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

General Information	
Analysis Type:	FEMP Analysis, Energy Project
Project Name:	Variable Speed Pump vs. Constant Speed Pump
Project Location:	Kansas
Analyst:	Fabian Philip Schmidt
Base Date:	1-Apr-12
Service Date:	1-Apr-12
Study Period:	20 years 0 months (April 1, 2012 through March 31, 2032)
Discount Rate:	3.50%
Discounting Convention:	End-of-Year

Discount and Escalation Rates are NOMINAL (inclusive of general inflation)

Case 2 - Heat Exchanger Valve Open

Base Case - Worthington D-824 Constant Speed Pump

*

Initial Cost Data (not Discounted)
Initial Capital Costs

(adjusted for price escalation)	
Initial Capital Costs for All Components:	$6,500

Component: Initial Costs

Cost-Phasing

Date	Portion	Yearly Cost
1-Apr-12	100%	$6,500
	------------	------------
Total (for Component)		$6,500

Energy Costs: Electricity	

(base-year dollars)

Average Annual Usage	Price/Unit	Average Annual Cost	Average Annual Demand	Average Annual Rebate
43,620.5 kWh	$0.079	$3,446	$480	$0

Water Costs: Make up Water Cost	

(base-year dollars)

	Average Annual Usage		
Water	Units/Year	Price/Unit	Average Annual Cost
@ Summer Rates	2,055,900.0 Gal	$0.00287	$5,900
@ Winter Rates	4,391,860.0 Gal	$0.00287	$12,605

Life-Cycle Cost Analysis		
	Present Value	Annual Value
Initial Capital Costs	$6,500	$457

Energy Costs	Present Value	Annual Value
Energy Consumption Costs	$53,250	$3,747
Energy Demand Charges	$7,417	$522
Energy Utility Rebates	$0	$0
	------------	------------
Subtotal (for Energy):	$60,667	$4,269

Water Usage Costs	$275,720	$19,402
Water Disposal Costs	$0	$0

Operating, Maintenance & Repair Costs		
Component: Initial Costs	Present Value	Annual Value
Annually Recurring Costs	$20,000	$1,407
Non-Annually Recurring Costs	$2,000	$141
	------------	------------
Subtotal (for OM&R):	$22,000	$1,548

Replacements to Capital Components	Present Value	Annual Value
Component: Initial Costs	$2,000	$141
	------------	------------
Subtotal (for Replacements):	$2,000	$141

Residual Value of Original Capital Components	Present Value	Annual Value
Component: Initial Costs	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

Residual Value of Capital Replacements	Present Value	Annual Value
Component: Initial Costs	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

	Present Value	Annual Value
Total Life-Cycle Cost	$366,887	$25,817

Alternative: Grundfos CRE 15-3 Variable Speed Pump

Initial Cost Data (not Discounted)

Initial Capital Costs

(adjusted for price escalation)

Initial Capital Costs for All Components:	$15,000

Component:

Cost-Phasing

Date	Portion	Yearly Cost
1-Apr-12	100%	$15,000
	------------	------------
Total (for Component)		$15,000

Energy Costs: Electricity

(base-year dollars)

Average Annual Usage	Price/Unit	Average Annual Cost	Average Annual Demand	Average Annual Rebate
49,410.4 kWh	$0.079	$3,903	$480	$0

Water Costs: Make up Water Cost

(base-year dollars)

	Average Annual Usage		
Water	Units/Year	Price/Unit	Average Annual Cost
@ Summer Rates	2,055,900.0 Gal	$0.00287	$5,900
@ Winter Rates	4,391,860.0 Gal	$0.00287	$12,605

Life-Cycle Cost Analysis		
	Present Value	Annual Value
Initial Capital Costs	$15,000	$1,056

Energy Costs	Present Value	Annual Value
Energy Consumption Costs	$60,318	$4,244
Energy Demand Charges	$7,417	$522
Energy Utility Rebates	$0	$0
	------------	------------
Subtotal (for Energy):	$67,735	$4,766

Water Usage Costs	$275,720	$19,402
Water Disposal Costs	$0	$0

Operating, Maintenance & Repair Costs		
Component:	Present Value	Annual Value
Annually Recurring Costs	$20,000	$1,407
Non-Annually Recurring Costs	$4,000	$281
	------------	------------
Subtotal (for OM&R):	$24,000	$1,689

Replacements to Capital Components	Present Value	Annual Value
Component:	$2,000	$141
	------------	------------
Subtotal (for Replacements):	$2,000	$141

Residual Value of Original Capital Components	Present Value	Annual Value
Component:	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

Residual Value of Capital Replacements	Present Value	Annual Value
Component:	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

	Present Value	Annual Value
Total Life-Cycle Cost	$384,455	$27,053

Appendix M: Case 2 with Heat Exchanger Valve Closed – Method A – Detailed Life Cycle Cost Report [23]

NIST BLCC 5.3-12: Detailed LCC Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

General Information	
Analysis Type:	FEMP Analysis, Energy Project
Project Name:	Variable Speed Pump vs. Constant Speed Pump
Project Location:	Kansas
Analyst:	Fabian Philip Schmidt
Base Date:	1-Apr-12
Service Date:	1-Apr-12
Study Period:	20 years 0 months (April 1, 2012 through March 31, 2032)
Discount Rate:	3.50%
Discounting Convention:	End-of-Year

Discount and Escalation Rates are NOMINAL (inclusive of general inflation)

Case 2 - Heat Exchanger Valve Closed - Method A

Base Case - Worthington D-824 Constant Speed Pump

Initial Cost Data (not Discounted)
Initial Capital Costs

(adjusted for price escalation)	
Initial Capital Costs for All Components:	$6,500

Component: Initial Costs

Cost-Phasing

Date	Portion	Yearly Cost
1-Apr-12	100%	$6,500
	------------	------------
Total (for Component)		$6,500

Energy Costs: Electricity	

(base-year dollars)

Average Annual Usage	Price/Unit	Average Annual Cost	Average Annual Demand	Average Annual Rebate
32,879.0 kWh	$0.079	$2,597	$480	$0

Water Costs: Make up Water Cost	

(base-year dollars)

	Average Annual Usage		
Water	Units/Year	Price/Unit	Average Annual Cost
@ Summer Rates	2,055,900.0 Gal	$0.00287	$5,900
@ Winter Rates	4,391,860.0 Gal	$0.00287	$12,605

Life-Cycle Cost Analysis

	Present Value	Annual Value
Initial Capital Costs	$6,500	$457

Energy Costs	Present Value	Annual Value
Energy Consumption Costs	$40,137	$2,824
Energy Demand Charges	$7,417	$522
Energy Utility Rebates	$0	$0
	------------	------------
Subtotal (for Energy):	$47,554	$3,346

Water Usage Costs	$275,720	$19,402
Water Disposal Costs	$0	$0

Operating, Maintenance & Repair Costs		
Component: Initial Costs	Present Value	Annual Value
Annually Recurring Costs	$20,000	$1,407
Non-Annually Recurring Costs	$2,000	$141
	------------	------------
Subtotal (for OM&R):	$22,000	$1,548

Replacements to Capital Components	Present Value	Annual Value
Component: Initial Costs	$2,000	$141
	------------	------------
Subtotal (for Replacements):	$2,000	$141

Residual Value of Original Capital Components	Present Value	Annual Value
Component: Initial Costs	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

Residual Value of Capital Replacements	Present Value	Annual Value
Component: Initial Costs	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

	Present Value	Annual Value
Total Life-Cycle Cost	$353,775	$24,894

Alternative: Grundfos CRE 15-3 Variable Speed Pump

Initial Cost Data (not Discounted)

Initial Capital Costs

(adjusted for price escalation)

Initial Capital Costs for All Components:	$15,000

Component:

Cost-Phasing

Date	Portion	Yearly Cost
1-Apr-12	100%	$15,000
	------------	------------
Total (for Component)		$15,000

Energy Costs: Electricity

(base-year dollars)

Average Annual Usage	Price/Unit	Average Annual Cost	Average Annual Demand	Average Annual Rebate
24,037.1 kWh	$0.079	$1,899	$480	$0

Water Costs: Make up Water Cost	

(base-year dollars)

Water	Average Annual Usage Units/Year	Price/Unit	Average Annual Cost
@ Summer Rates	2,055,900.0 Gal	$0.00287	$5,900
@ Winter Rates	4,391,860.0 Gal	$0.00287	$12,605

Life-Cycle Cost Analysis		
	Present Value	Annual Value
Initial Capital Costs	$15,000	$1,056

Energy Costs	Present Value	Annual Value
Energy Consumption Costs	$29,343	$2,065
Energy Demand Charges	$7,417	$522
Energy Utility Rebates	$0	$0
	------------	------------
Subtotal (for Energy):	$36,760	$2,587

Water Usage Costs	$275,720	$19,402
Water Disposal Costs	$0	$0

Operating, Maintenance & Repair Costs		
Component:	Present Value	Annual Value
Annually Recurring Costs	$20,000	$1,407
Non-Annually Recurring Costs	$4,000	$281
	------------	------------
Subtotal (for OM&R):	$24,000	$1,689

Replacements to Capital Components	Present Value	Annual Value
Component:	$2,000	$141
	------------	------------
Subtotal (for Replacements):	$2,000	$141

Residual Value of Original Capital Components	Present Value	Annual Value
Component:	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

Residual Value of Capital Replacements	Present Value	Annual Value
Component:	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

	Present Value	Annual Value
Total Life-Cycle Cost	$353,481	$24,874

Appendix M.1: Case 2 with Heat Exchanger Valve Closed – Method B - Detailed Life Cycle Cost Report [23]

NIST BLCC 5.3-12: Detailed LCC Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

General Information	
Analysis Type:	FEMP Analysis, Energy Project
Project Name:	Variable Speed Pump vs. Constant Speed Pump
Project Location:	Kansas
Analyst:	Fabian Philip Schmidt
Base Date:	1-Apr-12
Service Date:	1-Apr-12
Study Period:	20 years 0 months (April 1, 2012 through March 31, 2032)
Discount Rate:	3.50%
Discounting Convention:	End-of-Year

Discount and Escalation Rates are NOMINAL (inclusive of general inflation)

Case 2 - Heat Exchanger Valve Closed - Method B

Base Case - Worthington D-824 Constant Speed Pump

Initial Cost Data (not Discounted)
Initial Capital Costs

(adjusted for price escalation)	
Initial Capital Costs for All Components:	$6,500

Component: Initial Costs

Cost-Phasing

Date	Portion	Yearly Cost
1-Apr-12	100%	$6,500
	------------	------------
Total (for Component)		$6,500

Energy Costs: Electricity	

(base-year dollars)

Average Annual Usage	Price/Unit	Average Annual Cost	Average Annual Demand	Average Annual Rebate
30,957.0 kWh	$0.079	$2,446	$480	$0

Water Costs: Make up Water Cost	

(base-year dollars)

	Average Annual Usage		
Water	Units/Year	Price/Unit	Average Annual Cost
@ Summer Rates	2,055,900.0 Gal	$0.00287	$5,900
@ Winter Rates	4,391,860.0 Gal	$0.00287	$12,605

Life-Cycle Cost Analysis

	Present Value	Annual Value
Initial Capital Costs	$6,500	$457

Energy Costs	Present Value	Annual Value
Energy Consumption Costs	$37,791	$2,659
Energy Demand Charges	$7,417	$522
Energy Utility Rebates	$0	$0
	------------	------------
Subtotal (for Energy):	$45,208	$3,181

Water Usage Costs	$275,720	$19,402
Water Disposal Costs	$0	$0

Operating, Maintenance & Repair Costs		
Component: Initial Costs	Present Value	Annual Value
Annually Recurring Costs	$20,000	$1,407
Non-Annually Recurring Costs	$2,000	$141
	------------	------------
Subtotal (for OM&R):	$22,000	$1,548

Replacements to Capital Components	Present Value	Annual Value
Component: Initial Costs	$2,000	$141
	------------	------------
Subtotal (for Replacements):	$2,000	$141

Residual Value of Original Capital Components	Present Value	Annual Value
Component: Initial Costs	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

Residual Value of Capital Replacements	Present Value	Annual Value
Component: Initial Costs	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

	Present Value	Annual Value
Total Life-Cycle Cost	$351,428	$24,729

Alternative: Grundfos CRE 15-3 Variable Speed Pump

Initial Cost Data (not Discounted)

Initial Capital Costs

(adjusted for price escalation)

Initial Capital Costs for All Components:	$15,000

Component:

Cost-Phasing

Date	Portion	Yearly Cost
1-Apr-12	100%	$15,000
	------------	------------
Total (for Component)		$15,000

Energy Costs: Electricity

(base-year dollars)

Average Annual Usage	Price/Unit	Average Annual Cost	Average Annual Demand	Average Annual Rebate
20,423.5 kWh	$0.079	$1,613	$480	$0

Water Costs: Make up Water Cost

(base-year dollars)

	Average Annual Usage		
Water	**Units/Year**	**Price/Unit**	**Average Annual Cost**
@ Summer Rates	2,055,900.0 Gal	$0.00287	$5,900
@ Winter Rates	4,391,860.0 Gal	$0.00287	$12,605

Life-Cycle Cost Analysis		
	Present Value	Annual Value
Initial Capital Costs	$15,000	$1,056

Energy Costs	Present Value	Annual Value
Energy Consumption Costs	$24,932	$1,754
Energy Demand Charges	$7,417	$522
Energy Utility Rebates	$0	$0
	------------	------------
Subtotal (for Energy):	$32,349	$2,276

Water Usage Costs	$275,720	$19,402
Water Disposal Costs	$0	$0

Operating, Maintenance & Repair Costs		
Component:	Present Value	Annual Value
Annually Recurring Costs	$20,000	$1,407
Non-Annually Recurring Costs	$4,000	$281
	------------	------------
Subtotal (for OM&R):	$24,000	$1,689

Replacements to Capital Components	Present Value	Annual Value
Component:	$2,000	$141
	------------	------------
Subtotal (for Replacements):	$2,000	$141

Residual Value of Original Capital Components	Present Value	Annual Value
Component:	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

Residual Value of Capital Replacements	Present Value	Annual Value
Component:	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

	Present Value	Annual Value
Total Life-Cycle Cost	$349,070	$24,563

Appendix N: Case 3 – Method A – Detailed Life Cycle Cost Report [23]

NIST BLCC 5.3-12: Detailed LCC Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

General Information	
Analysis Type:	FEMP Analysis, Energy Project
Project Name:	Variable Speed Pump vs. Constant Speed Pump
Project Location:	Kansas
Analyst:	Fabian Philip Schmidt
Base Date:	1-Apr-12
Service Date:	1-Apr-12
Study Period:	20 years 0 months (April 1, 2012 through March 31, 2032)
Discount Rate:	3.50%
Discounting Convention:	End-of-Year

Discount and Escalation Rates are NOMINAL
(inclusive of general inflation)

Case 3 - Method A

Base Case - Worthington D-824 Constant Speed Pump

*

Initial Cost Data (not Discounted)

Initial Capital Costs

(adjusted for price escalation)	
Initial Capital Costs for All Components:	$6,500

Component: Initial Costs

Cost-Phasing

Date	Portion	Yearly Cost
1-Apr-12	100%	$6,500
	------------	------------
Total (for Component)		$6,500

Energy Costs: Electricity	

(base-year dollars)

Average Annual Usage	Price/Unit	Average Annual Cost	Average Annual Demand	Average Annual Rebate
42,426.8 kWh	$0.079	$3,352	$480	$0

Water Costs: Make up Water Cost	

(base-year dollars)

	Average Annual Usage		
Water	Units/Year	Price/Unit	Average Annual Cost
@ Summer Rates	2,055,900.0 Gal	$0.00287	$5,900
@ Winter Rates	4,391,860.0 Gal	$0.00287	$12,605

Life-Cycle Cost Analysis		
	Present Value	Annual Value
Initial Capital Costs	$6,500	$457

Energy Costs	Present Value	Annual Value
Energy Consumption Costs	$51,792	$3,645
Energy Demand Charges	$7,417	$522
Energy Utility Rebates	$0	$0
	------------	------------
Subtotal (for Energy):	$59,210	$4,166

Water Usage Costs	$275,720	$19,402
Water Disposal Costs	$0	$0

Operating, Maintenance & Repair Costs		
Component: Initial Costs	Present Value	Annual Value
Annually Recurring Costs	$20,000	$1,407
Non-Annually Recurring Costs	$2,000	$141
	------------	------------
Subtotal (for OM&R):	$22,000	$1,548

Replacements to Capital Components	Present Value	Annual Value
Component: Initial Costs	$2,000	$141
	------------	------------
Subtotal (for Replacements):	$2,000	$141

Residual Value of Original Capital Components	Present Value	Annual Value
Component: Initial Costs	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

Residual Value of Capital Replacements	Present Value	Annual Value
Component: Initial Costs	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

	Present Value	Annual Value
Total Life-Cycle Cost	$365,430	$25,714

Alternative: Grundfos CRE 15-3 Variable Speed Pump

Initial Cost Data (not Discounted)

Initial Capital Costs

(adjusted for price escalation)

Initial Capital Costs for All Components:	$15,000

Component:

Cost-Phasing

Date	Portion	Yearly Cost
1-Apr-12	100%	$15,000
	------------	------------
Total (for Component)		$15,000

Energy Costs: Electricity

(base-year dollars)

Average Annual Usage	Price/Unit	Average Annual Cost	Average Annual Demand	Average Annual Rebate
8,827.5 kWh	$0.079	$697	$480	$0

Water Costs: Make up Water Cost

(base-year dollars)

	Average Annual Usage		
Water	Units/Year	Price/Unit	Average Annual Cost
@ Summer Rates	2,055,900.0 Gal	$0.00287	$5,900
@ Winter Rates	4,391,860.0 Gal	$0.00287	$12,605

Life-Cycle Cost Analysis		
	Present Value	Annual Value
Initial Capital Costs	$15,000	$1,056

Energy Costs	Present Value	Annual Value
Energy Consumption Costs	$10,776	$758
Energy Demand Charges	$7,417	$522
Energy Utility Rebates	$0	$0
	------------	------------
Subtotal (for Energy):	$18,193	$1,280

Water Usage Costs	$275,720	$19,402
Water Disposal Costs	$0	$0

Operating, Maintenance & Repair Costs		
Component:	Present Value	Annual Value
Annually Recurring Costs	$20,000	$1,407
Non-Annually Recurring Costs	$4,000	$281
	------------	------------
Subtotal (for OM&R):	$24,000	$1,689

Replacements to Capital Components	Present Value	Annual Value
Component:	$2,000	$141
	------------	------------
Subtotal (for Replacements):	$2,000	$141

Residual Value of Original Capital Components	Present Value	Annual Value
Component:	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

Residual Value of Capital Replacements	Present Value	Annual Value
Component:	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

	Present Value	Annual Value
Total Life-Cycle Cost	$334,914	$23,567

Appendix N.1: Case 3 – Method B – Detailed Life Cycle Cost Report [23]

NIST BLCC 5.3-12: Detailed LCC Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

General Information	
Analysis Type:	FEMP Analysis, Energy Project
Project Name:	Variable Speed Pump vs. Constant Speed Pump
Project Location:	Kansas
Analyst:	Fabian Philip Schmidt
Base Date:	1-Apr-12
Service Date:	1-Apr-12
Study Period:	20 years 0 months (April 1, 2012 through March 31, 2032)
Discount Rate:	3.50%
Discounting Convention:	End-of-Year

Discount and Escalation Rates are NOMINAL (inclusive of general inflation)

Case 3 - Method B

Base Case - Worthington D-824 Constant Speed Pump

*

Initial Cost Data (not Discounted)

Initial Capital Costs

(adjusted for price escalation)	
Initial Capital Costs for All Components:	$6,500

Component: Initial Costs

Cost-Phasing

Date	Portion	Yearly Cost
1-Apr-12	100%	$6,500
	------------	------------
Total (for Component)		$6,500

Energy Costs: Electricity	

(base-year dollars)

Average Annual Usage	Price/Unit	Average Annual Cost	Average Annual Demand	Average Annual Rebate
38,699.8 kWh	$0.079	$3,057	$480	$0

Water Costs: Make up Water Cost			

(base-year dollars)

	Average Annual Usage		
Water	Units/Year	Price/Unit	Average Annual Cost
@ Summer Rates	2,055,900.0 Gal	$0.00287	$5,900
@ Winter Rates	4,391,860.0 Gal	$0.00287	$12,605

Life-Cycle Cost Analysis		
	Present Value	Annual Value
Initial Capital Costs	$6,500	$457

Energy Costs	Present Value	Annual Value
Energy Consumption Costs	$47,243	$3,324
Energy Demand Charges	$7,417	$522
Energy Utility Rebates	$0	$0
	------------	------------
Subtotal (for Energy):	$54,660	$3,846

Water Usage Costs	$275,720	$19,402
Water Disposal Costs	$0	$0

Operating, Maintenance & Repair Costs		
Component: Initial Costs	Present Value	Annual Value
Annually Recurring Costs	$20,000	$1,407
Non-Annually Recurring Costs	$2,000	$141
	------------	------------
Subtotal (for OM&R):	$22,000	$1,548

Replacements to Capital Components	Present Value	Annual Value
Component: Initial Costs	$2,000	$141
	------------	------------
Subtotal (for Replacements):	$2,000	$141

Residual Value of Original Capital Components	Present Value	Annual Value
Component: Initial Costs	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

Residual Value of Capital Replacements	Present Value	Annual Value
Component: Initial Costs	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

	Present Value	Annual Value
Total Life-Cycle Cost	$360,880	$25,394

Alternative: Grundfos CRE 15-3 Variable Speed Pump

Initial Cost Data (not Discounted)

Initial Capital Costs

(adjusted for price escalation)

Initial Capital Costs for All Components:	$15,000

Component:

Cost-Phasing

Date	Portion	Yearly Cost
1-Apr-12	100%	$15,000
	------------	------------
Total (for Component)		$15,000

Energy Costs: Electricity

(base-year dollars)

Average Annual Usage	Price/Unit	Average Annual Cost	Average Annual Demand	Average Annual Rebate
8,151.7 kWh	$0.079	$644	$480	$0

Water Costs: Make up Water Cost

(base-year dollars)

	Average Annual Usage		
Water	**Units/Year**	**Price/Unit**	**Average Annual Cost**
@ Summer Rates	2,055,900.0 Gal	$0.00287	$5,900
@ Winter Rates	4,391,860.0 Gal	$0.00287	$12,605

Life-Cycle Cost Analysis		
	Present Value	Annual Value
Initial Capital Costs	$15,000	$1,056

Energy Costs	Present Value	Annual Value
Energy Consumption Costs	$9,951	$700
Energy Demand Charges	$7,417	$522
Energy Utility Rebates	$0	$0
	------------	------------
Subtotal (for Energy):	$17,368	$1,222

Water Usage Costs	$275,720	$19,402
Water Disposal Costs	$0	$0

Operating, Maintenance & Repair Costs		
Component:	Present Value	Annual Value
Annually Recurring Costs	$20,000	$1,407
Non-Annually Recurring Costs	$4,000	$281
	------------	------------
Subtotal (for OM&R):	$24,000	$1,689

Replacements to Capital Components	Present Value	Annual Value
Component:	$2,000	$141
	------------	------------
Subtotal (for Replacements):	$2,000	$141

Residual Value of Original Capital Components	Present Value	Annual Value
Component:	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

Residual Value of Capital Replacements	Present Value	Annual Value
Component:	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

	Present Value	Annual Value
Total Life-Cycle Cost	$334,089	$23,509

Appendix O: Case 4 – Considering Heat Exchanger, Detailed Life Cycle Cost Report [23]

NIST BLCC 5.3-12: Detailed LCC Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

General Information	
Analysis Type:	FEMP Analysis, Energy Project
Project Name:	Variable Speed Pump vs. Constant Speed Pump
Project Location:	Kansas
Analyst:	Fabian Philip Schmidt
Base Date:	1-Apr-12
Service Date:	1-Apr-12
Study Period:	20 years 0 months (April 1, 2012 through March 31, 2032)
Discount Rate:	3.50%
Discounting Convention:	End-of-Year

Discount and Escalation Rates are NOMINAL (inclusive of general inflation)

Case 4 - Considering Heat Exchanger for D-824

Base Case - Worthington D-824 Constant Speed Pump

*

Initial Cost Data (not Discounted)

Initial Capital Costs

(adjusted for price escalation)	
Initial Capital Costs for All Components:	$6,500

Component: Initial Costs

Cost-Phasing

Date	Portion	Yearly Cost
1-Apr-12	100%	$6,500
	------------	------------
Total (for Component)		$6,500

Energy Costs: Electricity	

(base-year dollars)

Average Annual Usage	Price/Unit	Average Annual Cost	Average Annual Demand	Average Annual Rebate
33,001.5 kWh	$0.079	$2,607	$480	$0

Water Costs: Make up Water Cost	

(base-year dollars)

	Average Annual Usage		
Water	Units/Year	Price/Unit	Average Annual Cost
@ Summer Rates	1,696,280.0 Gal	$0.00287	$4,868
@ Winter Rates	4,391,860.0 Gal	$0.00287	$12,605

Life-Cycle Cost Analysis		
	Present Value	Annual Value
Initial Capital Costs	$6,500	$457

Energy Costs	Present Value	Annual Value
Energy Consumption Costs	$40,286	$2,835
Energy Demand Charges	$7,417	$522
Energy Utility Rebates	$0	$0
	------------	------------
Subtotal (for Energy):	$47,704	$3,357

Water Usage Costs	$260,342	$18,320
Water Disposal Costs	$0	$0

Operating, Maintenance & Repair Costs		
Component: Initial Costs	Present Value	Annual Value
Annually Recurring Costs	$20,000	$1,407
Non-Annually Recurring Costs	$2,000	$141
	------------	------------
Subtotal (for OM&R):	$22,000	$1,548

Replacements to Capital Components	Present Value	Annual Value
Component: Initial Costs	$2,000	$141
	------------	------------
Subtotal (for Replacements):	$2,000	$141

Residual Value of Original Capital Components	Present Value	Annual Value
Component: Initial Costs	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

Residual Value of Capital Replacements	Present Value	Annual Value
Component: Initial Costs	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

	Present Value	Annual Value
Total Life-Cycle Cost	$338,546	$23,823

Alternative: Grundfos CRE 15-3 Variable Speed Pump

Initial Cost Data (not Discounted)

Initial Capital Costs

(adjusted for price escalation)

Initial Capital Costs for All Components:	$15,000

Component:

Cost-Phasing

Date	Portion	Yearly Cost
1-Apr-12	100%	$15,000
	------------	------------
Total (for Component)		$15,000

Energy Costs: Electricity

(base-year dollars)

Average Annual Usage	Price/Unit	Average Annual Cost	Average Annual Demand	Average Annual Rebate
10,227.4 kWh	$0.079	$808	$480	$0

Water Costs: Make up Water Cost

(base-year dollars)

	Average Annual Usage		
Water	Units/Year	Price/Unit	Average Annual Cost
@ Summer Rates	1,696,280.0 Gal	$0.00287	$4,868
@ Winter Rates	4,391,860.0 Gal	$0.00287	$12,605

Life-Cycle Cost Analysis		
	Present Value	Annual Value
Initial Capital Costs	$15,000	$1,056

Energy Costs	Present Value	Annual Value
Energy Consumption Costs	$12,485	$879
Energy Demand Charges	$7,417	$522
Energy Utility Rebates	$0	$0
	------------	------------
Subtotal (for Energy):	$19,902	$1,400

Water Usage Costs	$260,342	$18,320
Water Disposal Costs	$0	$0

Operating, Maintenance & Repair Costs		
Component:	Present Value	Annual Value
Annually Recurring Costs	$20,000	$1,407
Non-Annually Recurring Costs	$4,000	$281
	------------	------------
Subtotal (for OM&R):	$24,000	$1,689

Replacements to Capital Components	Present Value	Annual Value
Component:	$2,000	$141
	------------	------------
Subtotal (for Replacements):	$2,000	$141

Residual Value of Original Capital Components	Present Value	Annual Value
Component:	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

Residual Value of Capital Replacements	Present Value	Annual Value
Component:	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

	Present Value	Annual Value
Total Life-Cycle Cost	$321,245	$22,605

Appendix P: Case 4- Not Considering Heat Exchanger, Detailed Life Cycle Cost Report [23]

NIST BLCC 5.3-12: Detailed LCC Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

General Information	
Analysis Type:	FEMP Analysis, Energy Project
Project Name:	Variable Speed Pump vs. Constant Speed Pump
Project Location:	Kansas
Analyst:	Fabian Philip Schmidt
Base Date:	1-Apr-12
Service Date:	1-Apr-12
Study Period:	20 years 0 months (April 1, 2012 through March 31, 2032)
Discount Rate:	3.50%
Discounting Convention:	End-of-Year

Discount and Escalation Rates are NOMINAL (inclusive of general inflation)

Case 4 - NOT Considering Heat Exchanger for D-824

Base Case - Worthington D-824 Constant Speed Pump

*

Initial Cost Data (not Discounted)

Initial Capital Costs

(adjusted for price escalation)	
Initial Capital Costs for All Components:	$6,500

Component: Initial Costs

Cost-Phasing

Date	Portion	Yearly Cost
1-Apr-12	100%	$6,500
	------------	------------
Total (for Component)		$6,500

Energy Costs: Electricity	

(base-year dollars)

Average Annual Usage	Price/Unit	Average Annual Cost	Average Annual Demand	Average Annual Rebate
24,912.9 kWh	$0.079	$1,968	$480	$0

Water Costs: Make up Water Cost	

(base-year dollars)

	Average Annual Usage		
Water	Units/Year	Price/Unit	Average Annual Cost
@ Summer Rates	1,696,280.0 Gal	$0.00287	$4,868
@ Winter Rates	4,391,860.0 Gal	$0.00287	$12,605

Life-Cycle Cost Analysis		
	Present Value	Annual Value
Initial Capital Costs	$6,500	$457

Energy Costs	Present Value	Annual Value
Energy Consumption Costs	$30,412	$2,140
Energy Demand Charges	$7,417	$522
Energy Utility Rebates	$0	$0
	------------	------------
Subtotal (for Energy):	$37,830	$2,662

Water Usage Costs	$260,342	$18,320
Water Disposal Costs	$0	$0

Operating, Maintenance & Repair Costs		
Component: Initial Costs	Present Value	Annual Value
Annually Recurring Costs	$20,000	$1,407
Non-Annually Recurring Costs	$2,000	$141
	------------	------------
Subtotal (for OM&R):	$22,000	$1,548

Replacements to Capital Components	Present Value	Annual Value
Component: Initial Costs	$2,000	$141
	------------	------------
Subtotal (for Replacements):	$2,000	$141

Residual Value of Original Capital Components	Present Value	Annual Value
Component: Initial Costs	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

Residual Value of Capital Replacements	Present Value	Annual Value
Component: Initial Costs	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

	Present Value	Annual Value
Total Life-Cycle Cost	$328,672	$23,128

Alternative: Grundfos CRE 15-3 Variable Speed Pump

Initial Cost Data (not Discounted)

Initial Capital Costs

(adjusted for price escalation)

Initial Capital Costs for All Components:	$15,000

Component:

Cost-Phasing

Date	Portion	Yearly Cost
1-Apr-12	100%	$15,000
	------------	------------
Total (for Component)		$15,000

Energy Costs: Electricity

(base-year dollars)

Average Annual Usage	Price/Unit	Average Annual Cost	Average Annual Demand	Average Annual Rebate
10,227.4 kWh	$0.079	$808	$480	$0

Water Costs: Make up Water Cost

(base-year dollars)

	Average Annual Usage		
Water	Units/Year	Price/Unit	Average Annual Cost
@ Summer Rates	1,696,280.0 Gal	$0.00287	$4,868
@ Winter Rates	4,391,860.0 Gal	$0.00287	$12,605

Life-Cycle Cost Analysis		
	Present Value	Annual Value
Initial Capital Costs	$15,000	$1,056

Energy Costs	Present Value	Annual Value
Energy Consumption Costs	$12,485	$879
Energy Demand Charges	$7,417	$522
Energy Utility Rebates	$0	$0
	------------	------------
Subtotal (for Energy):	$19,902	$1,400

Water Usage Costs	$260,342	$18,320
Water Disposal Costs	$0	$0

Operating, Maintenance & Repair Costs		
Component:	Present Value	Annual Value
Annually Recurring Costs	$20,000	$1,407
Non-Annually Recurring Costs	$4,000	$281
	------------	------------
Subtotal (for OM&R):	$24,000	$1,689

Replacements to Capital Components	Present Value	Annual Value
Component:	$2,000	$141
	------------	------------
Subtotal (for Replacements):	$2,000	$141

Residual Value of Original Capital Components	Present Value	Annual Value
Component:	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

Residual Value of Capital Replacements	Present Value	Annual Value
Component:	$0	$0
	------------	------------
Subtotal (for Residual Value):	$0	$0

	Present Value	Annual Value
Total Life-Cycle Cost	$321,245	$22,605

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