The techno-economical impact of reducing chilled water usage on a deep level gold mine

RJ van den Berg

22119272

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Supervisor: Prof M van Eldik

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ABSTRACT

Title: The techno-economical impact of reducing chilled water usage on a deep level gold mine

Author: Rudolph Johannes van den Berg

Supervisor: Prof. M van Eldik

Keywords: Motor cooling, chilled water usage reduction, financial savings

Deep level gold mines make use of refrigeration plants to chill water for use in underground operations. Operating these plants as well as pumping the used water back to surface result in significant costs. To reduce this operating cost of a deep level mine, an investigation into different areas of the operations was done to determine whether chilled water usage could be significantly reduced.

This study focusses specifically on reducing the chilled water usage at the underground dewatering pump motor coolers, as a significant amount of chilled water is consumed for cooling purposes. This study proposes alternative methods of cooling and discuss the physical implementation thereof. The three chilled water reduction strategies investigated include converting from an air-to-water motor cooling strategy to an air-to-air cooling method, installation of automated solenoid valves, and the use of clear water for motor cooling purposes.

By implementing these strategies at a case study mine the chilled water flow has been reduced by 50 l/s, which relates to a R 13.3 Million financial saving in terms of operational costs.

SAMEVATTING

Titel: Die tegno-ekonomiese impak van die vermindering in verkilde water verbruik op ‘n diep vlak goudmyn.

Outeur: Rudolph Johannes van den Berg

Studieleier: Prof. M van Eldik

Sleutelwoorde: Motorverkoeling, kouewater verbruiksvermindering, finansiële besparings

Goudmyne maak gebruik van verkoelingsaanlegte om water te verkil wat ondergrond gebruik word vir myn doeleindes. Die water wat ondergrond gebruik is moet dan weer na die oppervlak gepomp word. Die siklus wat die water volg gaan met hoë operasionelekostes gepaard as gevolg van die elektrisiteitsverbruik. In ‘n poging om hierdie kostes te verlaag is ‘n studie geloots om vas te stel of kouewaterverbruik veminder kan word in verskillende ondergrondse myngebiede.

Hierdie studie fokus spesifiek op die vermindering van kouewater verbruik vir die verkoeling van die motors van groot ondergrondse ontwateringspompe. ‘n Enorme hoeveelheid kouewater word verbruik vir hierdie doeleinde. Hierdie studie stel alternatiewe verkoelingsmetodes voor wat toegepas kan word om die pompe se motors te verkoel.

Drie inisiatiewe word voorgestel en nagevors in hierdie studie om ‘n finansiële besparing teweeg te bring. Eerstens om die waterverkoeling volledig te elimineer en te vervang met lugverkoeling, tweedens die installasie van automatiese kleppe wat die verkoelingswater beheer na aanleiding van die pomp se operasionele status, en derdens die gebruik van ‘n alternatiewe water bron vir verkoeling.

Deur die bogenoemde strategieë toe te pas by ‘n gevallestudie myn is die koue water verbuik verminder met 50 l/s. Die ooreenkomstige finansiële besparing in operasionele kostes is R13.3 miljoen.

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ABBREVIATIONS

#	–	Shaft
3CPS	–	3 Chamber Pump System
A/C	–	Air Cooler
ACP	–	Air Cooling Power index
BAC	–	Bulk Air Cooler
BPS	–	Booster Pump Station
DE	–	Drive End
DSM	–	Demand Side Management
EE	–	Energy Efficiency
HMI	–	Human Machine Interface
kW	–	Kilowatt
kWh	–	Kilowatt-hour
ML	–	Mega litre
MPa	–	Mega pascal
MW	–	Megawatt
MWh	–	Megawatt-hour
NDE	–	Non-Drive End
OEM	–	Original Equipment Manufacturer
P&ID	–	Piping and Instrumentation Diagram
PAT	–	Pump-As-Turbine
PLC	–	Programmable Logic Controller
PPCV	–	Pressure Profile Control Valve
PPM	–	Parts per million
PRV	–	Pressure Reducing Valve
RAW	–	Return Airway
SCADA	–	Supervisory Control and Data Acquisition
TOU	–	Time-Of-Use
VRT	–	Virgin Rock Temperature
VSD		Variable Speed Drive

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CHAPTER 1: INTRODUCTION

1.1 Background

Gold is an irreplaceable commodity in South Africa and its importance in the country's history and economy can never be overlooked. Gold is the commodity that earns South Africa a lot of foreign exchange and about 5% of the current global gold supply has its origins in South Africa (Chamber of mines South Africa; 2016). Mining gold in South Africa has become an excessively energy intensive operation due to the increasing depth of mining operations and the underground environmental conditions found at these extreme depths.

Electricity is the backbone of many enterprises in South Africa and it is often taken for granted. The importance of electricity is well emphasized and all of the economic sectors realize this when the supply is interrupted or load shedding takes place. Currently, South Africa is experiencing an energy crisis and energy efficient products and solutions need to be evaluated and implemented accordingly. Eskom generates around 95% of South Africa's total energy demand at a total of 41 995 MW (Eskom, 2014: 10). South Africa's generation consists of a number of technologies of which coal-fired power stations are the absolute majority, with the remainder of the technologies makes up less than 15% of the generation capacity. A breakdown of Eskom's generation technologies is shown in Figure 1.

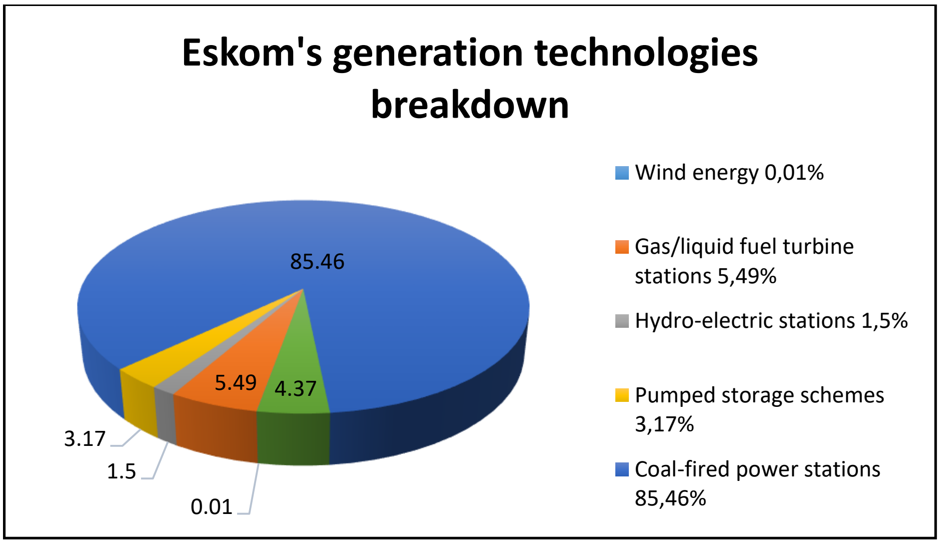

Figure 1 – Eskom's generation technologies breakdown (Botha, 2010: 1)

South Africa consumed 4328 kWh per capita in 2013, which is the most of all African countries (Worldbank; 2016), with Figure 2 showing the mining industry consuming 14.1% of the total generation capacity (Eskom, 2014:84). Figure 2 illustrates the different electricity consumer groups in South Africa and their respective contribution to the total consumption. Gold mining is a water-intensive operation which impacts the energy consumption of the total operation. As seen from Figure 3, refrigeration and pumping combined consume about 34% of a mine's energy annually (Botha, 2010: 3). This makes refrigeration and pumping ideal sectors to investigate for potential energy efficiency and reduction in energy consumption opportunities.

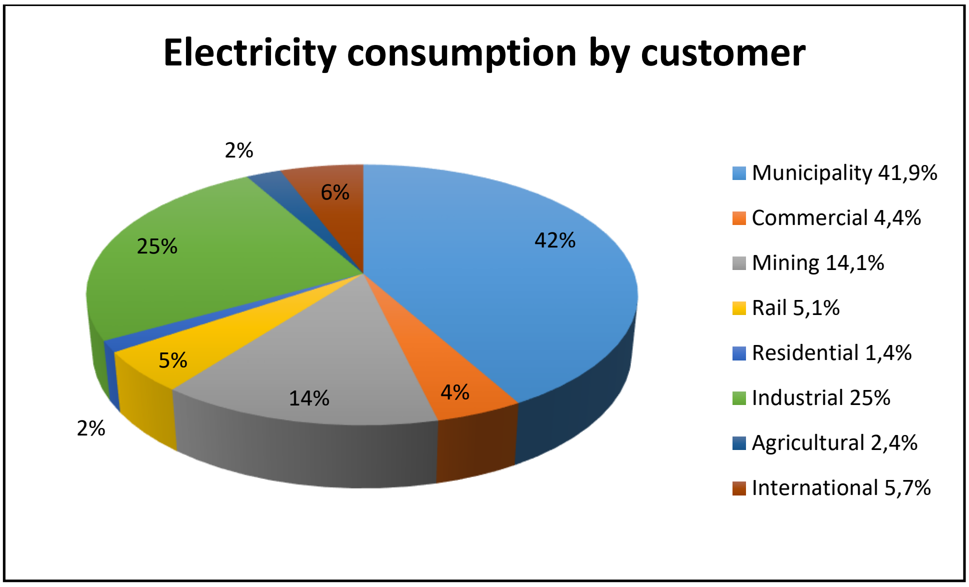

Figure 2 – Electricity consumption breakdown of South Africa (Eskom, 2014: 94)

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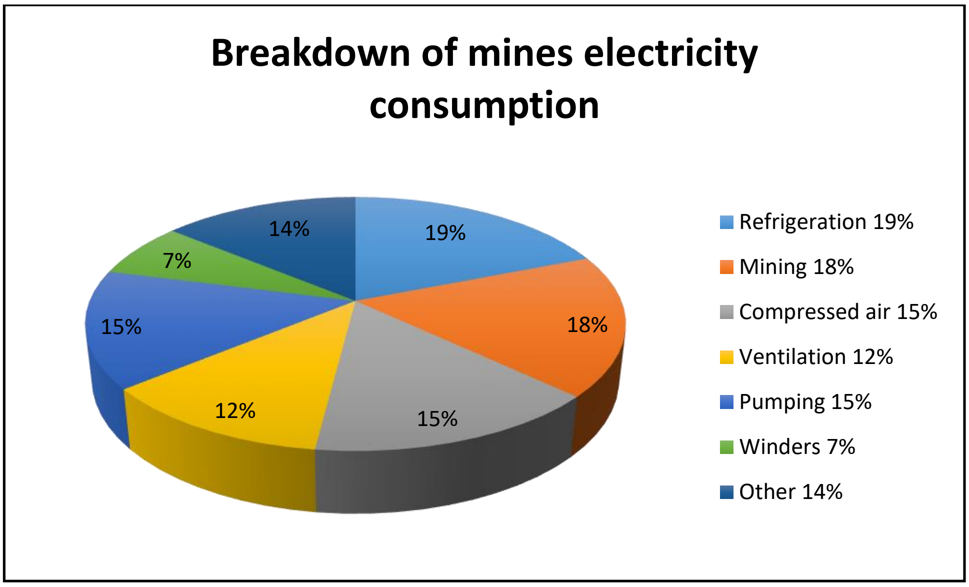

Figure 3 – Breakdown of mines electricity consumption (Cloete, 2015: 1)

1.2 Problem statement

South Africa has 8 of the world's 10 deepest mines, with the remaining two located in Canada (mining-technology, 2013). At these extreme depths, the environmental conditions can become unbearable with virgin rock temperatures reaching 65℃ (Stephenson, 1983:22). The underground workplace temperatures are regulated and must at all times be below certain set points that are governed to be safe and reasonably comfortable for daily work to commence in. The Air Cooling Power index (ACP) is a guideline used for the required cooling needed, with $300W/m^2$ shown to be sufficient for hard physical work to commence in an area (Swart, 2003: 5).

Global energy consumption is projected to increase by 57% from 2002 to 2025 (Le Roux, 2005: 1), with industrial energy usage accounting for one-third of this global consumption. As mentioned above, mining consumes 14.1% of South Africa's total generation capacity, with both the water reticulation and cooling systems on a deep level gold mine accounting for 34% of the total energy consumed by a mining operation (Du Plessis et al, 2013:312; Botha, 2010:3). Chilled water is, therefore, an expensive yet important part of deep level gold mining. However, any visit to a deep level gold mine reveals that a significant amount of chilled water is wasted or used inefficiently and ineffectively. A reduction in chilled water consumption should thus be of high priority for a South African gold mine due to the impact it has on their cost of production. This problem is further emphasized by the annual rising energy costs that are forecasted to continue for the years to come as shown from the historic increase in Figure 4.

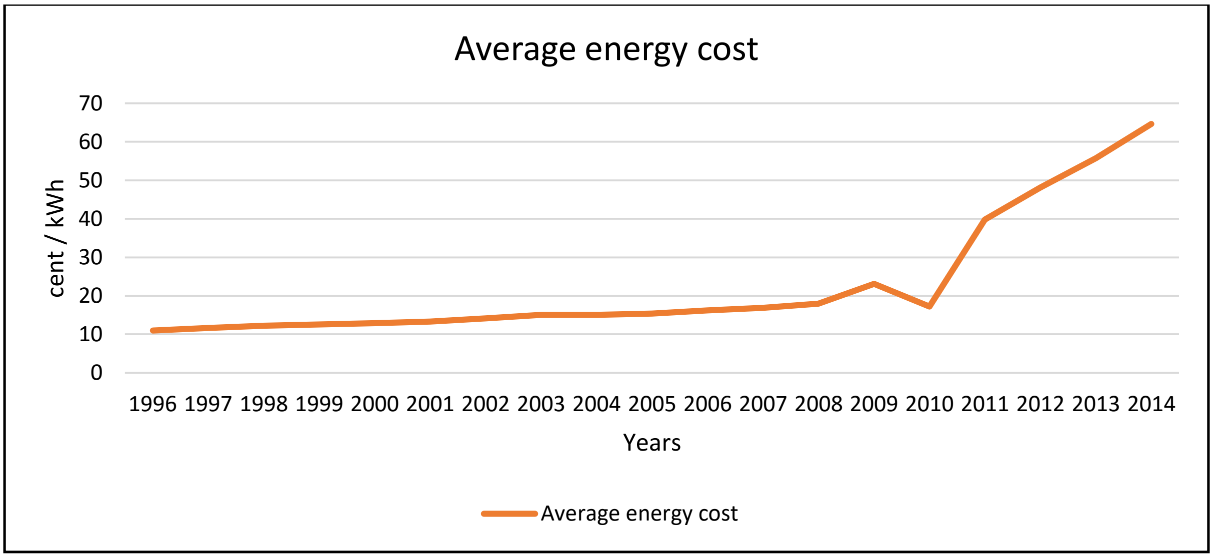

Figure 4 – Mining specific energy cost increase (Eskom; 2014)

Chilled water applied for cooling purposes are typically used in i) the bulk air cooler, ii) cooling cars or spot coolers, iii) high-pressure hoses used to spray and cool the rock faces, iv) cooling of the drilling machines and operations, and vi) the most important for this study being the pump motor coolers. Chilled water is not only used for cooling but is also used for other applications underground such as washing, jetting, sweeping operations, drilling and dust suppression or spraying (Stephenson, 1983: 21).

When the chilled water has passed through its relevant point of consumption, it gets dumped on the footwall or the floor, for the majority of the cases, and flows to the drains. The water then flows to the underground dams which are below the working levels where the chilled water was used, which brings about an immediate loss of head, as pumping stations and their allocated dams are located between 600 and 1000 meters vertically from each other (Botha, 2010:17).

The wastage or inefficient use of chilled water underground can be technical of nature as well as behavioural. Outdated designs and insufficient repairs to the water system are not able to adapt to changes and variations anymore and presents another wastage opportunity. Most water reticulation systems in the mines have been installed quite a number of years ago and are becoming old. Since the installation of the original piping and infrastructure, the operating conditions of the mines have changed.

There is a need to reduce the chilled water consumption with the aim of reducing the electricity cost, and improve the water reticulation system in ways that have not yet been investigated.

Innovative interventions and investigations need to be implemented to realize a reduction in electricity consumption.

1.3 Objective of the study

The objective of this study is to implement a number of interventions to reduce the chilled water consumption on a mine and therefore reduce the electricity cost to the mine.

By reducing the amount of chilled water that is consumed it will not only reduce the electricity cost but also assist in reducing the load on the pumping stations and the refrigeration plants, which increase the lifespan and also benefits the mine financially.

Underground pump motor cooling has been identified as a major consumer of chilled water, and this study will focus on reducing the chilled water consumed by means of three different technologies, namely:

- Conversion from chilled water cooling to open-circuit air cooling;
- Using clear water instead of chilled water;
- Implementation of an automated solenoid valve control methodology.

1.4 Outline of this dissertation

Chapter 2 Literature study

The literature study consists of a review of previous studies and a motivation for this study. The operation of a mine dewatering system will be described as well as the uses of chilled water underground. The different parts of a mine that have a direct effect on this study will also be investigated and described. The literature study is critical, comprehensive and relevant.

Chapter 3 Energy saving initiative 1

The air cooler initiative will be discussed on a technical basis and all the relevant aspects will be attended to in terms of the operation of the new system. The methodology behind the study and the approach taken will be discussed and the verification and validation of the initiative will be stated. The results will be quantified and conclusions and recommendations will be made.

Chapter 4 Energy saving initiative 2

The booster pump station initiative will be discussed on a technical basis and all the relevant aspects will be attended to on the operation of the new system. The methodology behind the study and the approach taken will be discussed and the verification and validation of the initiative will be stated. The results will be quantified and conclusions and recommendations will be made.

Chapter 5 Energy saving initiative 3

The automated solenoid valve initiative will be discussed on a technical basis and all the relevant aspects will be attended to on the operation of the new system. The methodology behind the study and the approach taken will be discussed and the verification and validation of the initiative will be stated. The results will be quantified and conclusions and recommendations will be made.

Chapter 6 Conclusion and recommendations

Concluding remarks will be shared and the outcome of the study will be discussed. Recommendations will be made in terms of prospective studies to follow.

CHAPTER 2: LITERATURE REVIEW

2.1 Preamble

Conserving energy in South Africa has become an inevitable part of our daily lives. To take part in the conservation drive, an effort has been made to reduce the amount of energy a typical gold mine consumes. By reducing the chilled water usage, a definite saving can be realized because of the direct correlation that exists between chilled water consumption and the electricity cost of a mine.

2.2 Overview of water reticulation systems on South African gold mines

Decades ago when the gold mines in South Africa were designed and built, the cost of electricity was one of the less important aspects the mining companies had to consider. This is because the cost of electricity was at such a low level in comparison to today and a surplus of electricity was available (Kenny; 2015: 5).

The depth of a mine and the number of pump stations required also vary according to the different shaft's challenges and requirements. As a mine develops to increasing depths over the years, more pumping stations are needed deeper down. Also, the pressure head that is developed due to the large distance of the vertical column going down can pose problems in terms of the pressure on the pipework of deeper levels. In most water reticulation systems this pressure needs to be dissipated, and typically done using either a turbine, Pump-As-Turbine (PAT), pressure reducing stations or open ended dumping of the water into an underground dam (van Antwerpen; 2004).

In the following figure a flow chart of a typical water reticulation system of a deep level gold mine can be seen:

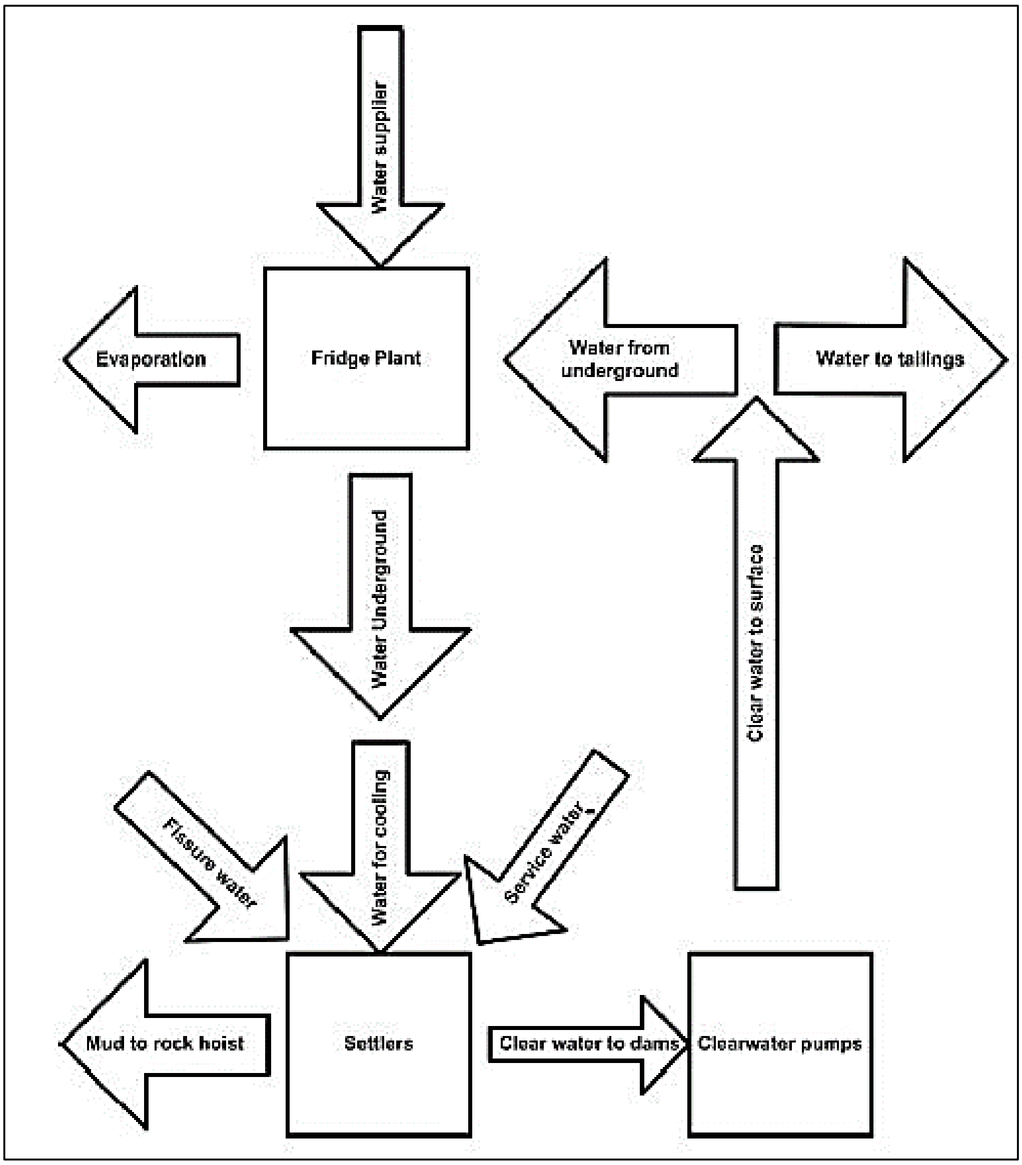

Figure 5 – Flowchart of a typical water reticulation system (Vosloo et al; 2012: 331)

The two types of water reticulation systems normally found in South African deep level gold mines are either a cascading dam system or a column feed system. Choosing the correct approach for a mine depends on the opportunities and possibilities each shaft possesses. At the mine forming part of this study, some shafts have cascading dam systems and some have column feed systems. Figure 6 illustrates the cascading dam system:

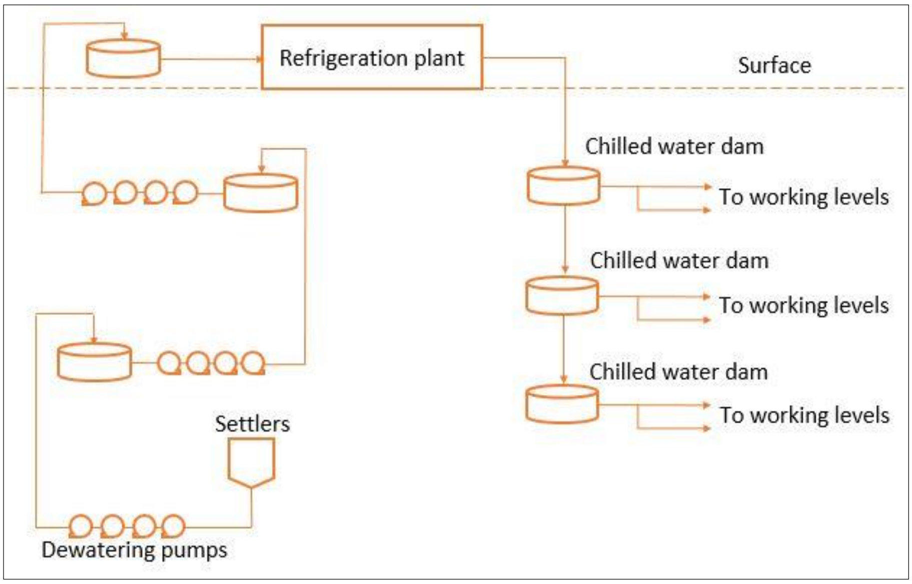

Figure 6 – Simple cascading dam system

All figures without references are either created by me or the photograph was taken by me personally. In a cascading dam system, a dam is fed with chilled water via another dam that is located higher up in the mine, and in turn feeds another dam on a lower level. From each of the dams the water is fed to the relevant working levels below that specific dam. After the water is used in the mining areas for various purposes it either runs naturally down to the settlers in certain areas or it's pumped to the nearest drain that also ends up in the settlers. In the settlers, the clear water rises and the mud sink down to the bottom from where the mud is pumped out. From the settlers, the clear water is sent down to the transfer level pump station after which the water gets pumped up to surface via various pump stations located on different levels.

The following figure (Figure 7) illustrates a simple layout of a column feed system.

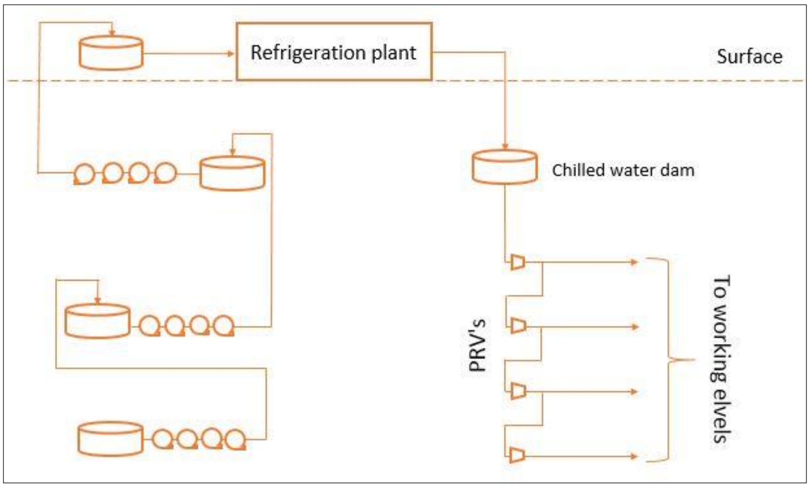

Figure 7 – Simple column feed system

The column feed system does not have as many chilled water dams as with the cascading dam system. From the chilled water dam, water is fed down the column to a certain level where a pressure reducing valve (PRV) reduces the water pressure so that it can be used on that level. After the PRV there also is a take-off column which runs down to the next working level where the same PRV strategy is repeated. The dewatering side of the water reticulation system works identically to a cascading dam system.

2.3 Water distribution

Water reticulation at a deep level gold mine can be split into two categories namely water distribution and dewatering. This section will discuss the water distribution of a typical gold mine to clarify all the elements that has an effect on the energy consumption and also to clarify what the chilled water is required for.

2.3.1 Refrigeration plant

To chill the water to temperatures useable by the mine in underground areas, a refrigeration plant is used. The fridge plant can be located either on surface or underground, depending on the geological challenges and the layout of the mine. The mental and physical needs of the mine workers also play a role in whether an underground fridge plant is necessary (Stanton; 2004: 187).

As can be seen in Figure 8 a fridge plant consists of three cycles, namely the main vapour compression cycle, a chilled water cycle on the evaporator side and a heat rejection cycle on the condenser side (Le Roux; 1990: 114). The chilled water is cooled down to a temperature which is predetermined by the mine, and is typically in the range from 3℃ to 4℃ (Le Roux; 1990: 123). This temperature range is essential to compensate for all the factors underground that have an effect on the temperature of the chilled water still going to the workplaces. If the initial discharge temperature is not within the prescribed range, the temperature of the water at the underground point of use will not be acceptable and all the interconnected service points will decrease in efficiency.

Equipment that is directly influenced by the supply temperature is the cooling cars used on different underground levels to do localised air cooling. The workings of the cooling cars will be discussed in more details later in this chapter:

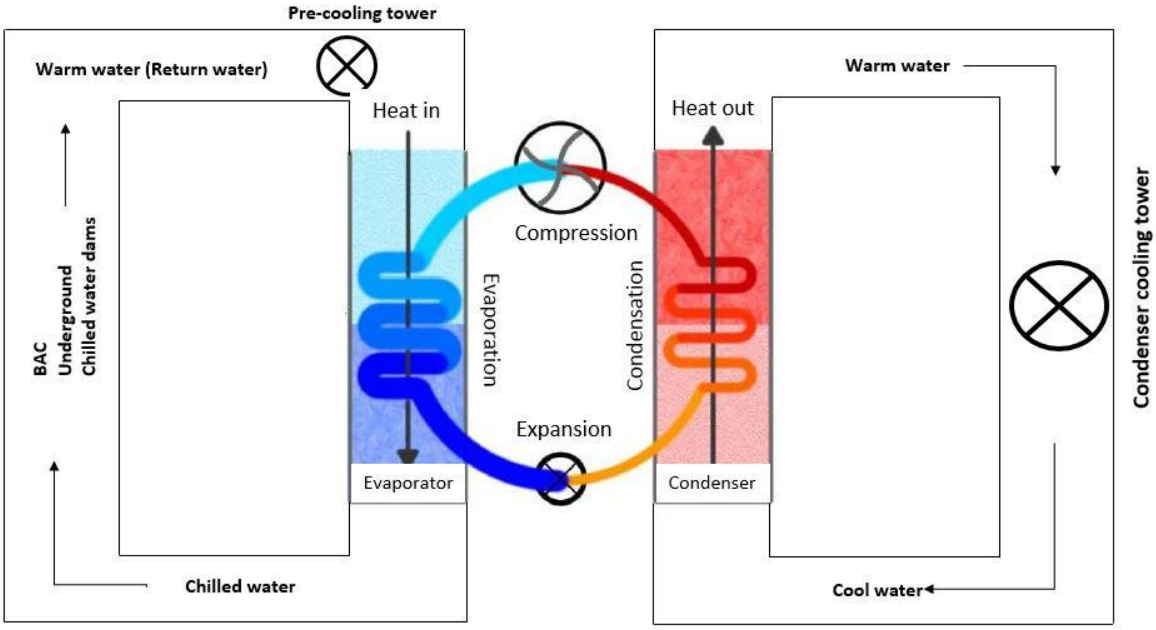

Figure 8 – Water cycles and vapour compression cycle of a fridge plant (Adapted from Murad; 2012)

The chilled water is sent to the bulk air cooler (BAC) and the underground chilled water dams. Upon return of the water from the underground operations and the BAC the water is at a higher temperature, typically around 27 to 33°C (Le Roux; 1990: 121). A pre-cooling tower cools the return water down to in the region of 17 to 20°C before the water then recirculates through the evaporator to be chilled again to between 3℃ and 4℃ (Prinsloo, 2004: 22).

2.3.2 Bulk air cooler

Part of the cooling duty of a deep level gold mine is to cool the ambient supply air down to a predetermined temperature (Le Roux; 1990: 121). The temperature of the supply air sent underground has a remarkable impact on the chilled water usage of a mine. To cool the ambient air that is sent underground a bulk air cooler (BAC) is used.

A BAC functions by passing air at ambient temperatures through spray chambers equipped with large fans (McPherson, 1993: 26). Inside the chambers, chilled water supplied from the fridge plant is sprayed by spray pumps. In Figure 9, a schematic top view diagram of a BAC can be seen to illustrate the concept.

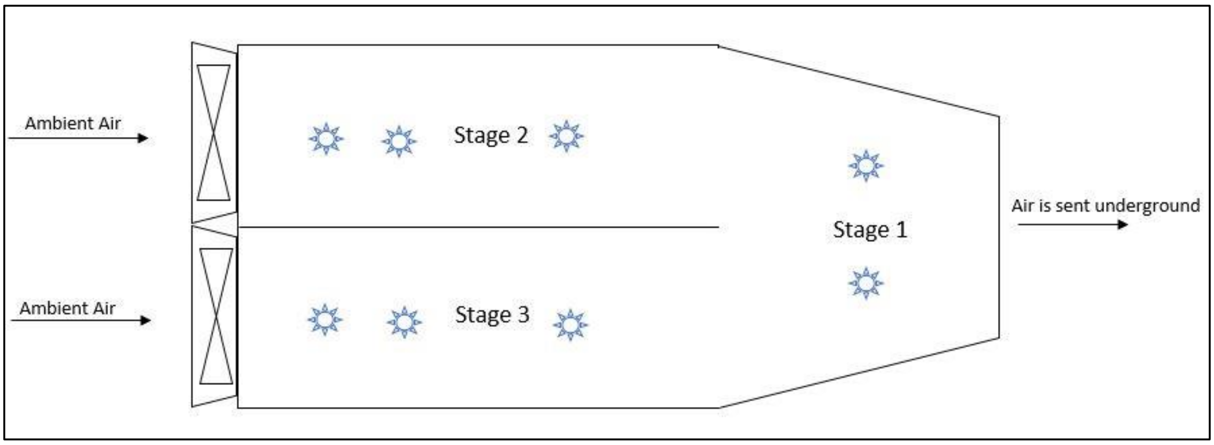

Figure 9 – Schematic diagram of a typical BAC (Top view)

Stage 1 will receive the coldest water straight from the fridge plant. This brings about a colder air temperature going underground as the air is already pre-cooled by stage 2 and stage 3. Stage 2 and stage 3 will use water for their sprayers from the sump of stage 1 because the water temperature in the sump of stage 1 is still at a sufficiently low temperature to be utilized and to have an effect on stage 2 and stage 3. This recirculated flow configuration also improves the efficiency of the system.

The sprayers are adjusted for an optimal spray with regards to droplet size and area coverage for maximum cooling effect (McPherson, 1993: 26). The air from stage 2 and stage 3 will combine in stage 1 and be further cooled before it is sent underground at a temperature of between 5℃ and 10℃.

In Figure 10 a photograph of a BAC inlet can be seen that has the same design as the schematic drawing above. The two left side fans are dedicated to stage 2 and the two right side fans are dedicated to stage 3.

Figure 10 – BAC with the same design as in the schematic drawing

2.3.3 Pump-as-turbines and Pelton turbines

This section discusses methods to generate electricity from the use of chilled water. Since this study forms part of an energy conservation drive it is noteworthy to look at generation as well. Chilled water that is piped down the mine creates an ideal opportunity to recover energy. The potential energy that is generated by the descent of the water down the mine, is normally dissipated as heat by the pressure reducing valves (PRV) (van Antwerpen; 2004: 563). A part of this energy can be recovered with the use of a turbine or a Pump-As-Turbine (PAT), also known as a reverse running centrifugal pump.

A commonly known type of turbine is a Pelton turbine. A Pelton turbine must be installed in the primary distribution pipe network directly above the primary chilled water dam as the operating principle of a Pelton turbine requires an atmospheric outlet pressure (Le Roux; 1990: 123). As a primary energy recovery initiative, a Pelton turbine has a number of advantages, whereas in secondary energy recovery systems the PAT has more advantages than a Pelton turbine (Laux; 1982; 2:23-7). A Pelton turbine discharges to atmospheric pressure although in the secondary water distribution system constant pressure needs to be maintained for the working areas. This eliminates the Pelton turbine as a viable option in secondary water distribution systems.

If it is possible to recover energy from the water going down a mine shaft, the column must be sized in such a manner that the velocity of the chilled water can be kept stable at around 3 m/s. If the friction losses are kept at a minimum, 3 m/s can be achieved and kept stable (Whillier; 1977: 183).

The advantages of a PAT system over the Pelton turbine is summarized by the following (Laux; 1982; 2: 23-7):

- Large, adjustable output range by altering the number of stages;
- Low manufacturing cost due to pump standardisation;
- Short delivery time due to pump mass production;
- Low runaway speed and smaller runaway speed than the Pelton;
- Mine maintenance personnel is familiar with the pump.

Thus, when factoring in the above-mentioned advantages, a PAT system is considered the best option to recover energy in a secondary water distribution system (Laux; 1982; 2:23-7; Torbin, 1989; 25(5): 811-8).

A layout of how a turbine can be implemented to save energy at a typical gold mine can be seen in the following figure.

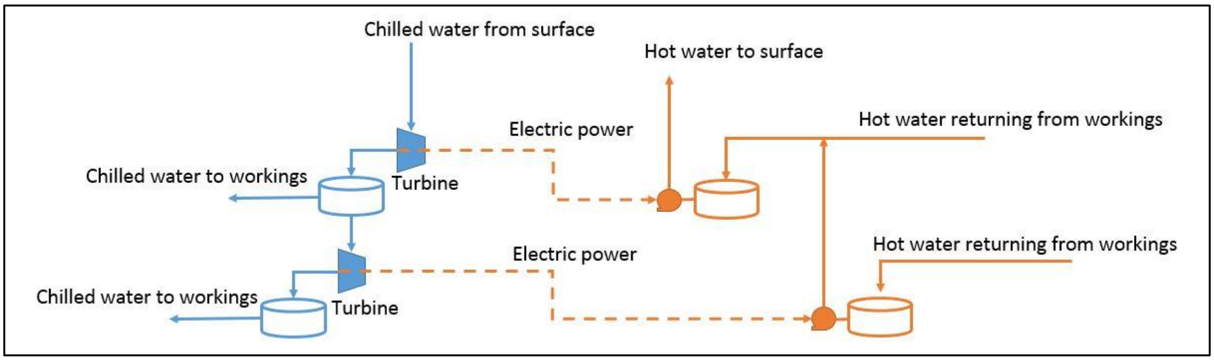

Figure 11 – Layout of turbines implemented to save energy (Adapted from Vosloo et al; 2012: 330)

2.3.4 Pressure reducing valves

Figure 12 – A PRV station (HPE; 2015)

As mentioned previously, chilled water that is piped down the shaft creates an enormous amount of hydraulic pressure in the columns (van Antwerpen; 2004: 563). Pressure Reducing Valves (PRV's), as shown above, are installed in strategic locations to reduce the pressure of the water at that specific level and/or working place, usually installed close to the shaft. In the right-hand side of Figure 7 an illustration of the locations of the PRV's can be seen.

2.4 Uses for chilled water underground

With the increasing virgin rock temperature (VRT) as the depth of mining increases, chilled water can be seen as a type of lifeline that makes working at these depths possible. Chilled water is used underground for a variety of purposes (Stephenson, 1983: 21) as will be discussed below.

2.4.1 Motor cooling

An integral part of the dewatering system, which will be discussed in section 2.5.3, is the dewatering pumps that are located in the pumping chambers underground. The dewatering pumps are multistage centrifugal pumps which are able to deliver a significant pressure head. The optimal distance for the pumping stations to be spaced from each other vertically is 600 m (De la Vergne; 2014: 188), however, they are often found beyond 1000m (IMWA; 1987: 20). These pumps are driven by electric motors which are typically in the range of 1110 kW up to 2750 kW, for the case study mine.

The pump motors are subjected to a large amount of load and strain from the pump axis and therefore needs sufficient cooling. The motors are typically equipped with a number of temperature sensors to continuously monitor the operating conditions of the motor.

The rotor of the electric motor has a fan mounted on the shaft of the motor, in some cases even two. The fan(s) is situated inside the casing of the motor and serves the purpose of circulating air through the windings and the motor (Siemens AG; 2009: 10). The water-to-air coolers that are commonly used to cool the motor are fitted on top and are connected to the chilled water lines.

Inside the water-to-air coolers, there are coils through which the chilled water is circulated. The air that is circulated by the internal fan of the motor passes over these coils and heat is exchanged between the warm air inside the motor and the chilled water. The air is cooled down due to the heat of the air being exchanged with the chilled water. The water is at a higher temperature leaving the water-to-air cooler.

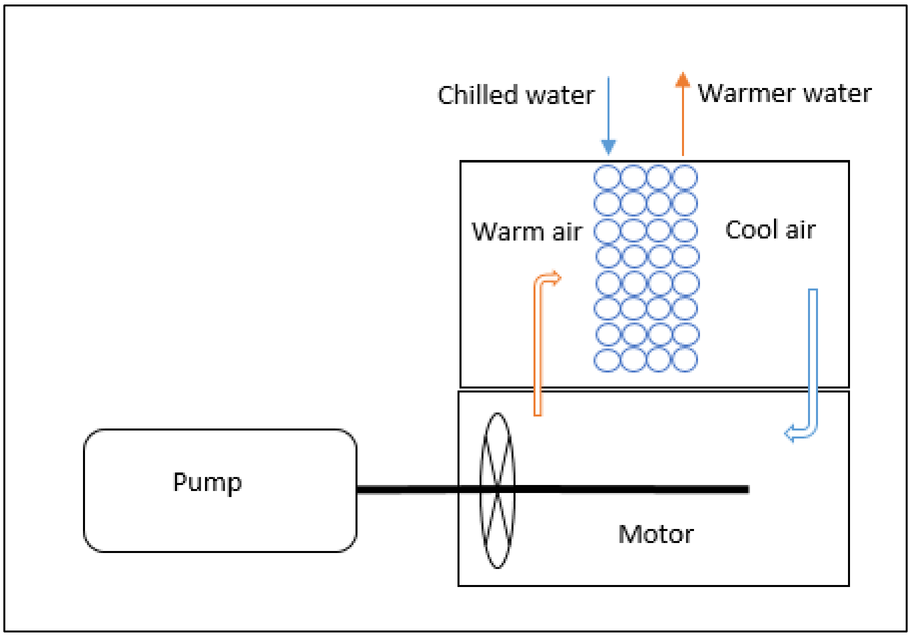

Figure 13 – Motor cooling diagram

The warmer water that is discharged by the cooler normally has no further use due to the temperature and needs to be pumped to surface through the dewatering system back to the fridge plant. The following picture shows the arrangement of the motor, motor cooler and pump.

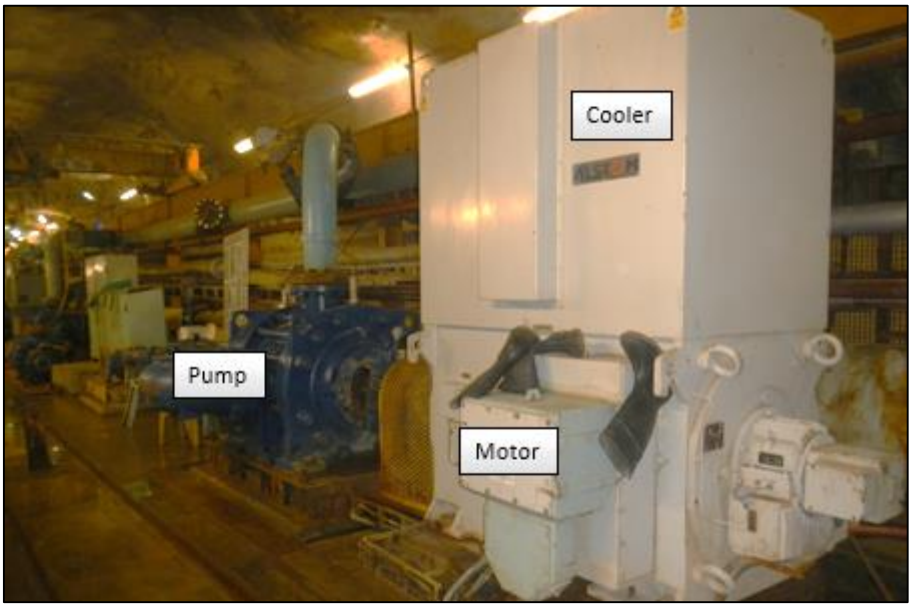

Figure 14 – Motor cooling arrangement

2.4.2 Cooling

The geothermal gradient in the area where the case study mine is located is typically 12 ℃ per kilometre of vertical depth (Stephenson, 1983: 22). This can result in a VRT of around 65℃ at a depth of over 3km. In the past when mines were still relatively shallow, normal ambient air ventilation provided enough cooling to ensure safe working conditions underground. With the mines currently developing to increasing depths following the dipping gold reef, using ventilation air alone is no longer sufficient. Water, on the other hand, has a higher specific heat than air, and chilled water has other purposes underground as well. Hence the common solution was to use chilled water for cooling purposes (Stephenson, 1983: 22).

To aid the cooling in areas where the ventilation is poor or the distance from the shaft is of great magnitude, the use of cooling cars becomes imminent. A cooling car is a cross flow heat exchanger consisting of coils that circulate chilled water through the inside. Air is cooled when drawn over the coils and thereby reduce the overall temperature in the area installed, such as the stopes or a warm haulage. An example of a cooling car, also known as a spot cooler, is shown in Figure 15.

Figure 15 – Cooling car (Manos; 2015)

2.4.3 Washing

From time to time washing is necessary as part of the mining maintenance schedule. The dams, for instance, need to be washed to clean out the mud and to ensure safe pumping operation. The pump stations, the outside of the pipes, the waiting areas and the stations are washed on a regular basis to keep a clean working environment and to ensure that an accident or injury could not occur due to the working areas being dirty. Washing also reduces the amount of dust present in the areas mentioned and thus reducing the risk of medical complications like Silicosis (ALA; 2015). In some instances, chilled water is used to wash these areas as clear water may not be available for use.

2.4.4 Jetting and sweeping

Figure 16 – Example of a water cannon (HPE; 2015)

Once the blasting is completed and the dust and heat levels are back under control, the miners can re-enter the working areas. Fine broken rock and ore are present as a result of the blast occurring. The rubble of rock and ore has to be transported underground and up to surface for further processing. In the stoping area, Figure 16, where the blast occurred, chilled water is used to move the waste rock and the ore to the loading area and the transportation network that is in place at the mine, which includes scraper winches, tips, hoppers and skips (Odendaal; 2016).

High-pressure chilled water is discharged at a high velocity to move the rock and ore and to clean out the stoping area before the drilling shift can commence their work. Water cannons and jets, Figure 17, accompanied by high water pressure are utilized for cleaning purposes, thus eliminating the use of shovels, scraper winches and brooms (Botha; 2014: 13).

Figure 17 – Example of a water jet (HPE; 2015)

2.4.5 Drilling and dust suppression

The focus of gold mining is to extract the precious metal from underground. To achieve this the ore has to be broken down into finer parts and transported to surface and to the gold processing plant where the gold will be extracted from the material through various processes. In order to break down and extract the ore from the solid structure that it is found underground, it has to be blasted with explosives. The explosives need to be planted into blast holes in the rock face to maximize the blasting effect. The blast hole is created by a drill and a drill operator as shown in Figure 18.

Upon drilling the blast holes an excess amount of heat and dust is generated which is an obvious safety hazard. The dust can cause discomfort and a disease, common in the mining industry, known as Silicosis (ALA; 2015). Chilled water is used to cool the drill bit and the surrounding areas through spraying the rock faces. Spraying also occurs after a blast to cool down the working area and to suppress the dust levels that are present, as shown in Figure 19 (de la Vergne: 2014: 213).

Figure 18 – Drill operation (Thompson; 2012)

Figure 19 – Dust suppression and rapid cooling after blast (Botha; 2014: 14)

2.5 Dewatering system of a deep level gold mine

After the chilled water have served its purpose, it needs to return to surface where it will be filtered and chilled to be sent underground again. This section covers the dewatering side of the mine which is responsible for the water to be pumped out.

2.5.1 Settlers

Figure 20 – Common cone settler (Perry; 1990: 1009-1025)

After the chilled water has been utilized underground it becomes part of the dewatering system. At the level directly above transfer level, the settlers will be located, and all of the used and dirty mine water is received by the settlers, as shown in Figure 20 (Perry; 1990: 1009-1025).

At the settlers a flocculent is added to the water while the water is in a turbulent flow. The turbulence provides satisfactory mixing of the water and the flocculent, if the flow velocity is at least 1 m/s and it is sustained for at least 30 seconds (de la Vergne; 2014: 204). The flocculent ensures that the pH level of the water is between 3 and 7 (Hansen et al; 2005). A typical flocculent that is implemented in the gold mining industry is lime (Tein; 2006). The pH level of the water causes the mud to increase its density and sink down to the bottom of the settler. The clear water rises to the top of the settler and into the clear water dams which means that the water can be pumped from the hot water dams by the dewatering pumping system (Botha: 2010; 16). The mud is sent to the mud dams from where mud pumps will extract it from the mine.

2.5.2 Hot water dams

At each pumping station, there are hot water dams, also known as clear water dams, located which forms part of the mine dewatering system. The dewatering pumps extract the water from the dams through a suction column, and pump it to the hot water return dams on a higher level (van Heerden, 2016). In some instances, the dams consist of sluice gates to control the water flow and to isolate a dam when the mine personnel is washing it out or doing maintenance. The hot water dams found underground are commonly over 1 ML in capacity (van Heerden, 2016).

2.5.3 Clear water pumps and mud pumps

"Any open pit and almost any underground mine is a vast sump collecting water. The water naturally tends to accumulate at the bottom of the working…" (De la Vergne; 2014:187). In deep-level gold mines the water does accumulate at the bottom of the shaft. After the water has been processed by the settler and the solids have accumulated at the bottom of the settler, the clear water flows to the hot water dams and can be pumped to the surface.

The clear water is stored in dams at the level or just above the pumping station. Clear water is extracted from the dam through a suction column and enters the multistage centrifugal pumps suction side. The clear water travels through the multiple stages of the centrifugal pump and building pressure with each progressive stage. The delivery side of the first impeller discharges into the suction side of the next impeller, and so forth (Engineers Edge, 2016).

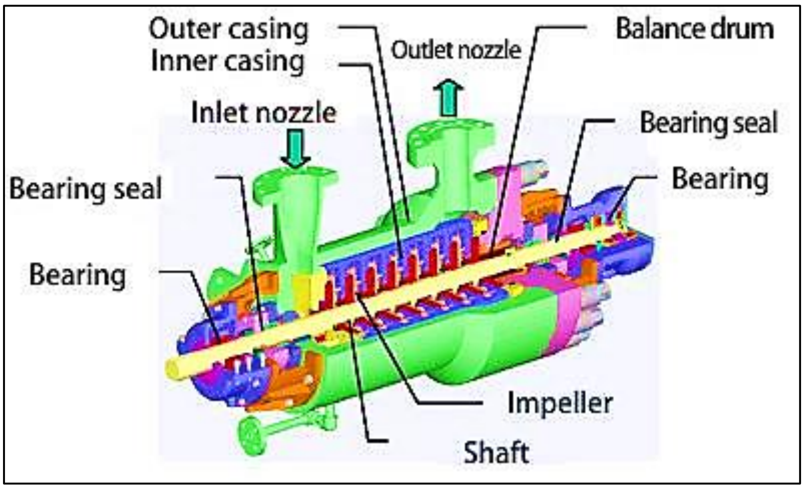

Figure 21 – Cutaway section view of a multistage centrifugal pump (Yukinaga: 2008)

The multistage centrifugal pumps, as shown in Figure 21, are necessary due to the large vertical distance the water has to travel. "Centrifugal pumps also are reliable, relatively compact and the multi-stages required for high heads can be directly driven with a single motor."(De la Vergne: 2014: 192).

2.5.4 Three chamber pump system (3CPS)

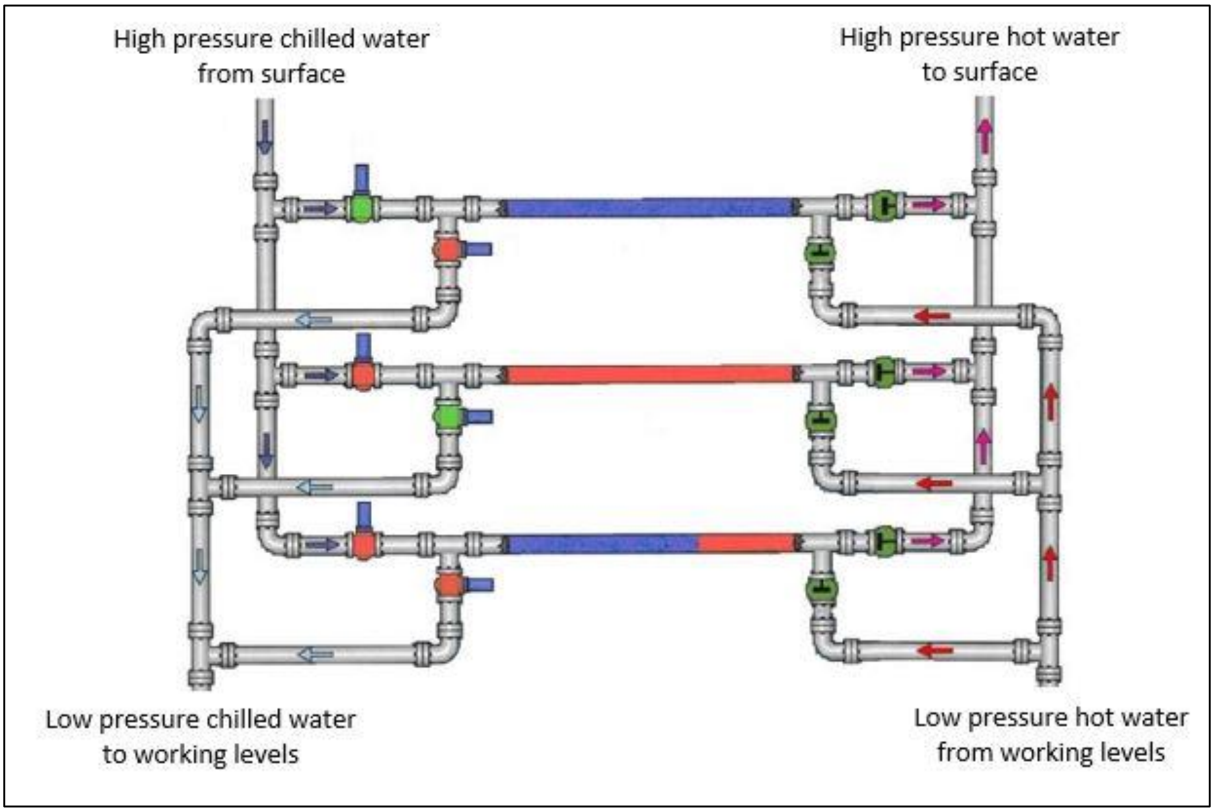

Figure 22 – Illustration of a 3CPS (adapted from van Niekerk: 2014: 2-27)

To aid the dewatering pumping system, the three chamber pump system (3CPS) has been intensively investigated and implemented at various sites (Rautenbach et al; 2005: 41). A 3CPS, as illustrated in Figure 22, is a dewatering pumping system that utilizes the head of the chilled water supply column that feeds the water underground from the surface. A 3CPS system uses a number of valves in a certain configuration together with the three chambers to displace hot water from underground mine workings with the high-pressure chilled water being fed underground (Vosloo; 2008: 63). A 3CPS operates on the basic principle of a U-tube and acts as the interface between the chilled water that is being sent underground and the hot service water that has to be pumped back to the surface (Fraser et al; 2007: 51-54).

The 3CPS was named after the three chambers that it uses to exchange potential energy between the hot and the cold sides. The 3CPS system also consists of a booster pump and a filler pump which fills the columns and overcome the friction in the columns which aids the U-tube effect (Biffi et al; 2010: 298). The benefit of the 3CPS is most definitely the efficiency thereof and as a result of that, it only uses a small amount of electrical energy. Three chamber pump systems have an efficiency of between 90% and 95%, which effectively means that it only uses 5% to 10% electricity supply (Vosloo; 2008: 66). The 3CPS system thus uses far less electrical energy than a multistage centrifugal pumping station due to the energy recovery principal that it operates on. The incoming chilled water does experience a slight increase in temperature due to the mixing with warmer water. When considering that the system pumps water out of the mine using limited electricity, it is negligible when compared to the enormous energy savings that the 3CPS realises (Le Roux;2005 : 74).

2.6 Different approaches to reduce electricity cost

With the South African gold mines classified under the Megaflex tariff structure, a vast number of interventions and initiatives have been implemented to benefit from the TOU tariff structure. The different strategies of Demand Side Management (DSM) include load shifting, peak clipping and energy efficiency.

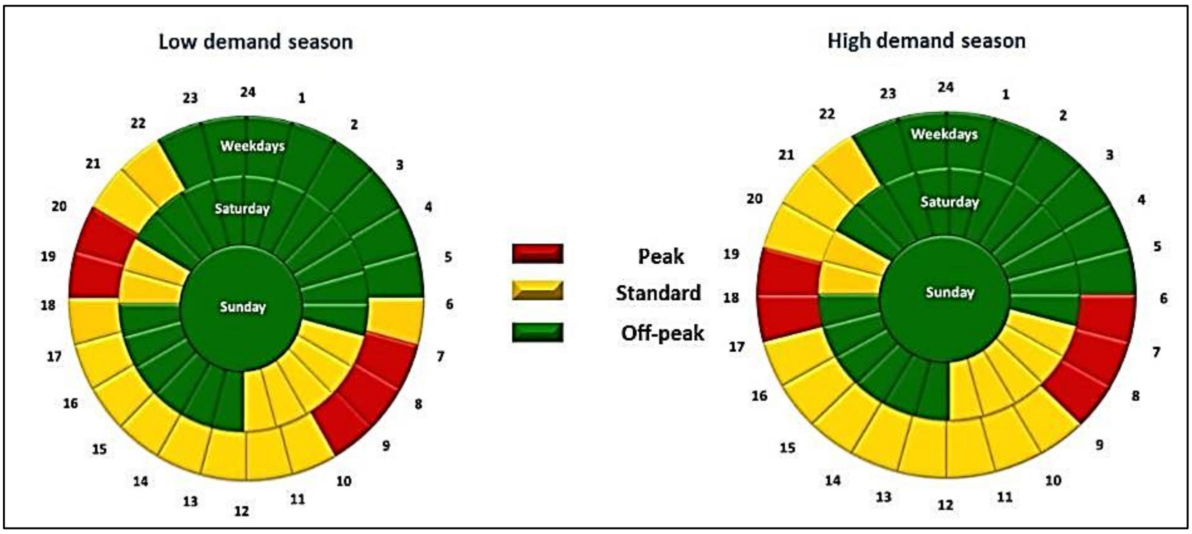

Figure 23 – Megaflex variable pricing wheel (Eskom, 2015/2016)

Table 1 lists the different tariffs of the Megaflex structure from Figure 23, where the high demand season refers to the months of June, July and August, with the low demand season making up the rest of the year.

Table 1 – *Megaflex tariffs (Eskom, 2014/2015)*

High Demand Season	Time of day	Low Demand Season
254.12 c/kWh	Peak	89.02 c/kWh
83.32 c/kWh	Standard	64.11 c/kWh
49.40 c/kWh	Off-peak	43.99 c/kWh

2.6.1 Load shifting

Eskom's more expensive peak times are from 07:00 up to 10:00 and in the evening from 18:00 to 20:00. To avoid paying these higher tariffs in the peak times, a strategy known as load shifting can be implemented.

Load shifting is a priority task of DSM (Tang et al; 2014:1). To be able to shift the load a storage facility needs to be readily available. This storage facility will typically be a dam in the case of mining applications. During the off-peak and/or standard times of the tariff structure, the preparation for the load shifting must be done. For a refrigeration plant, this will entail loading the available chilled water dams to a maximum level so that load shifting can take place. When 18:00 arrives accompanied by the most expensive tariff, the refrigeration plant is shut down completely and a single pump can feed the stored chilled water to the Bulk Air Cooler (BAC) as well as other underground operations. Another example of load shifting is at the mine dewatering pumps, where the pumps have to empty the underground hot water dams to a minimum level before the expensive tariff time of 18:00 arrives. When it does arrive the pumps will then be stopped and the dams will then gradually fill up with water until the pumps will be started again after 20:00. A typical power usage profile can be seen in Figure 24 along with the effect of load shifting. It must be noted that load shifting is an energy neutral strategy that simply shifts the load on the plants or machinery into a different time zone and price tariff, it does not save energy or reduce energy consumption.

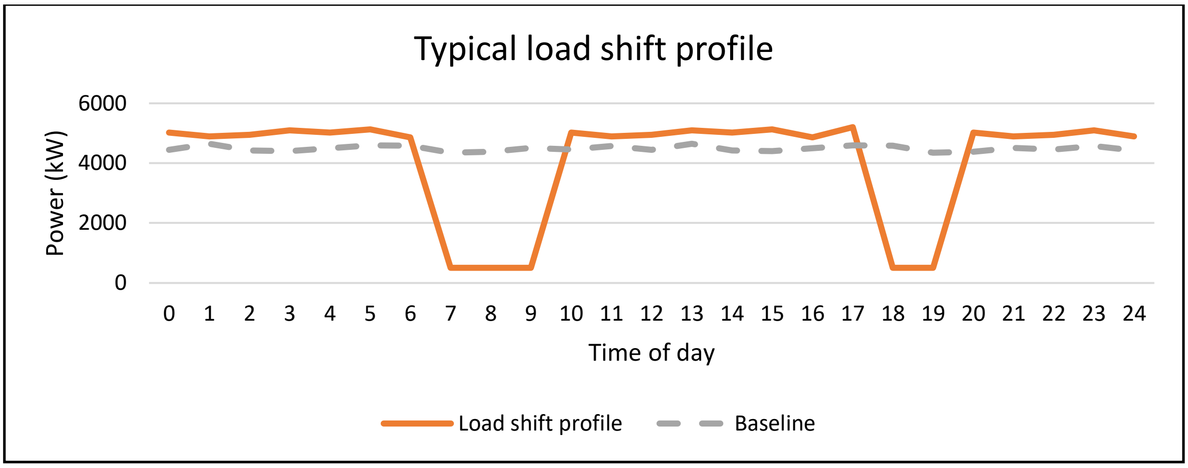

Figure 24 – Load shift profile against Baseline profile

A novel approach to load shifting was investigated with regards to the mining industry by Le Roux (2005). His approach consisted of controlling the clear water pumps at an optimum point where financial costs can be minimised with load shifting. Load shifting on dewatering pumps and fridge plants have been investigated by Van Niekerk (2014) to build a model as to predict which DSM strategy will benefit marginal mines the most. Load shifting is also possible on underground fridge plants as concluded by Strydom-Bouwer (2008). Van Niekerk investigated the possibility and the value of simulating DSM solutions before implementation (Van Niekerk; 2014). Another load shifting study has been done by Prinsloo and he concluded that energy cost can be reduced by means of shifting the load of a complex mine pumping system (Prinsloo: 2004; 23). Oosthuizen investigated the optimisation of the pumping schedule at a deep level gold mine to realise financial savings according to the tariff structure (Oosthuizen; 2012: i). The human factor in pump schedule optimisation underground can be problematic. Richter conducted research and compared the results of implementing an automated DSM pumping schedule and operating the pumping schedule manually. He concluded that an automated pumping system operating on an optimised schedule can realise 45% more financial savings than attempting to do it manually (Richter; 2008: 76).

2.6.2 Energy efficiency

Energy efficiency focuses on reducing the average electricity demand of an operation. Various energy efficiency initiatives can result in a significant saving, like for instance focusing on reducing the chilled water consumption and thereby reducing the electricity consumption of a mine. Where load shifting only has an impact during certain times of the day, energy efficiency is more likely to have an effect over the full span of the average day (Cousins; 2010). The impact of a typical energy efficiency initiative is illustrated in Figure 25.

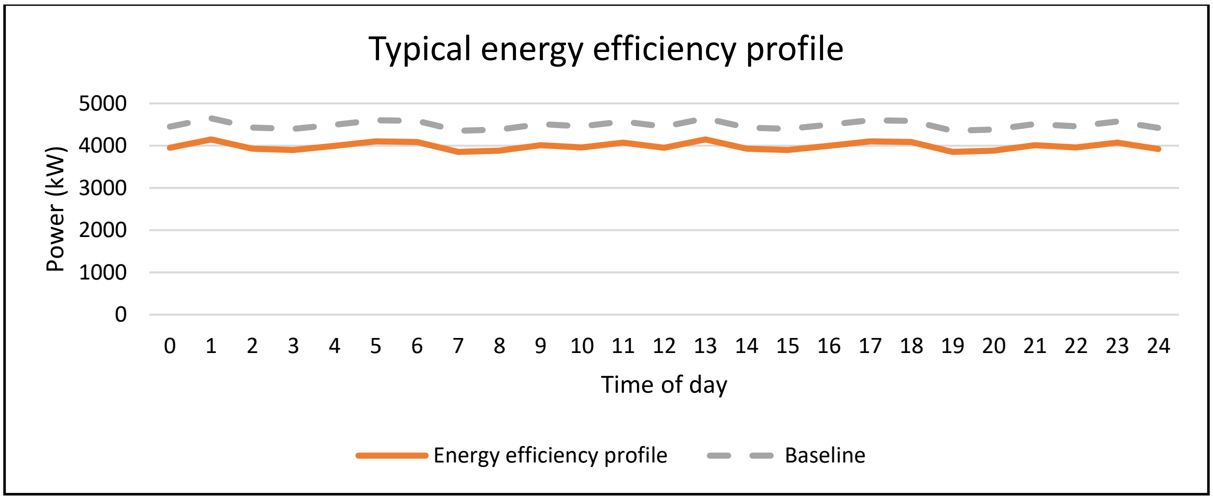

Figure 25 – Typical energy efficiency profile against the baseline profile

It was found by Vosloo that the efficiency of total systems can be improved. If the pumping layout of a case study mine is investigated and examined thoroughly, the possibility is there that the overall efficiency can be improved (Vosloo; 2008: 57). Murray also compiled models to calculate pump efficiencies which can be applied to implement energy efficiency. He also said that by implementing energy efficiency strategies a mine can reduce their costs, conserve energy and maintain profitability (Murray; 2008: 1). In a study by Govender, he mentioned that energy efficiency could "assist companies to reduce energy consumption, aid local power utilities in a crisis and maintain production levels". According to Govender energy efficiency also holds economic and environmental benefits for a mine (Govender; 2009: iv). Another energy efficiency investigation was done by Van Greunen and he concluded that implementing a variable speed drive control system on a mine cooling system can realise financial savings due to reduction in energy consumption (Van Greunen; 2012).

2.6.3 Peak clipping

Peak clipping can be defined as the reduction of electricity consumption by the reduction of the peak demand. The maximum demand period over the span of a day is known as the peak. Peak clipping is usually implemented during the peak times of Eskom's Megaflex tariff structure. It is important to note that peak clipping might have an impact on production because it is typically done by switching off a process or a system for a certain amount of time. However the ideal way is to achieve it without affecting production (Govender; 2008: 2).

Peak clipping reduces the total demand compared to where load shifting does not reduce the demand. Load shifting simply shifts the load into another tariff band, but the total energy consumed during the span of a day stays the same. An illustration of peak clipping can be seen in Figure 26.

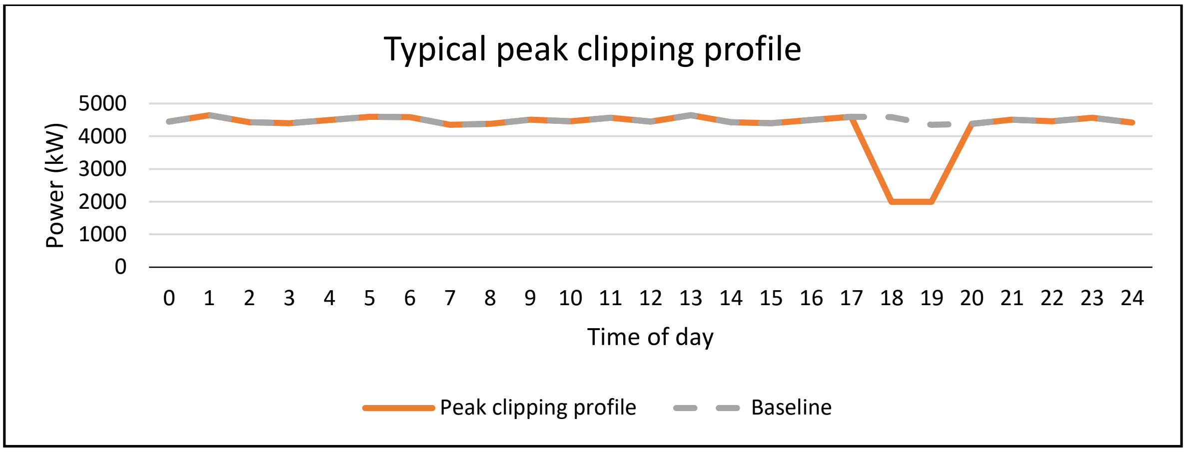

Figure 26 – Peak clipping profile against Baseline profile

2.7 Summary

Extensive research exists regarding all the above mentioned topics and how to reduce the cost of deep level gold mines. However, there still remains a lack of research into whether an alternative method for pump motor cooling can be financially beneficial. The current literature does not cover the aspect of whether the current cooling arrangement as found underground can be altered or improved to obtain a direct cost saving. Hence, this study will investigate whether alterations to pump motor cooling systems are possible and more importantly if they are financially beneficial.

CHAPTER 3: CHILLED WATER REDUCTION

3.1 Preamble

The electricity consumption of a deep level gold mine can be directly impacted by reducing the amount of pumping that is required as well as the total amount of water that has to be chilled by the refrigeration plants. Three techniques to reduce the chilled water usage will be investigated in this study.

3.2 Reduction of the chilled water usage

Problem areas regarding wastage of chilled water exist in all gold mines in South Africa. The current situation in the mines offers significant cost savings through innovative interventions. Problematic areas can be identified by comparing the monthly water usage of a specific shaft against the sum of the ore and waste rock that is hoisted. Mine development, as well as production, are both chilled water consuming activities (Botha; 2010:28).

Data has been obtained from the mine under investigation which consists of the planned vs. actual water usage as well as the planned vs. actual ore mined figures. This data can be used to calculate and plot the actual cubic metres of water consumed per ton hoisted against what was planned and budgeted for, using equations 1 and 2 (Van Zyl; 2014). The planned consumption figure is realistic as it is calculated on the mine's historic data. A lot of factors are included in the calculation such as depth of the mine, active areas etc. The planned figure will not be discussed in detail as it is not the focus of this study but was merely applied as an indicator of performance. A previous study conducted stated that the average South African gold mine should use 2.6 m^3 water per ton of ore hoisted (Vosloo; 2008: 52). The figure that Vosloo benchmarked is an average figure calculated over different depths of mine and different mining methods.

$$[\frac{m^3\ water}{ton\ hoisted}]_{actual} = \frac{Actual\ m^3\ water\ consumed}{Actual\ tons\ hoisted} \quad [1]$$

$$[\frac{m^3\ water}{ton\ hoisted}]_{planned} = \frac{Planned\ m^3\ water\ consumed}{Planned\ tons\ hoisted} \quad [2]$$

The case study mine consist of 4 shafts (A#, B#, C# and D#). All shafts are production shafts and they contribute equally to the mine's production call. The 4 shafts mentioned are all clustered together and are interlinked at some levels.

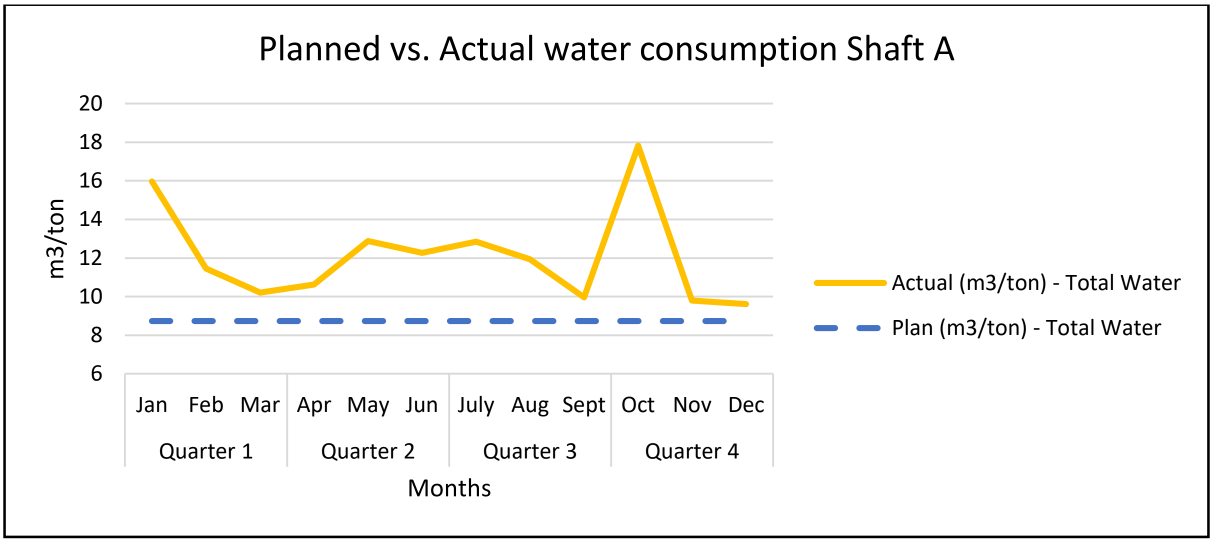

Figure 27 – Planned versus actual water consumption of Shaft A

Figure 27 shows that Shaft A (A#) consumed a significant amount of chilled water and it exceeds the planned water consumption by an alarming average of 37.4 % for the year that the data was provided. Shaft A clearly poses an opportunity for water reduction studies.

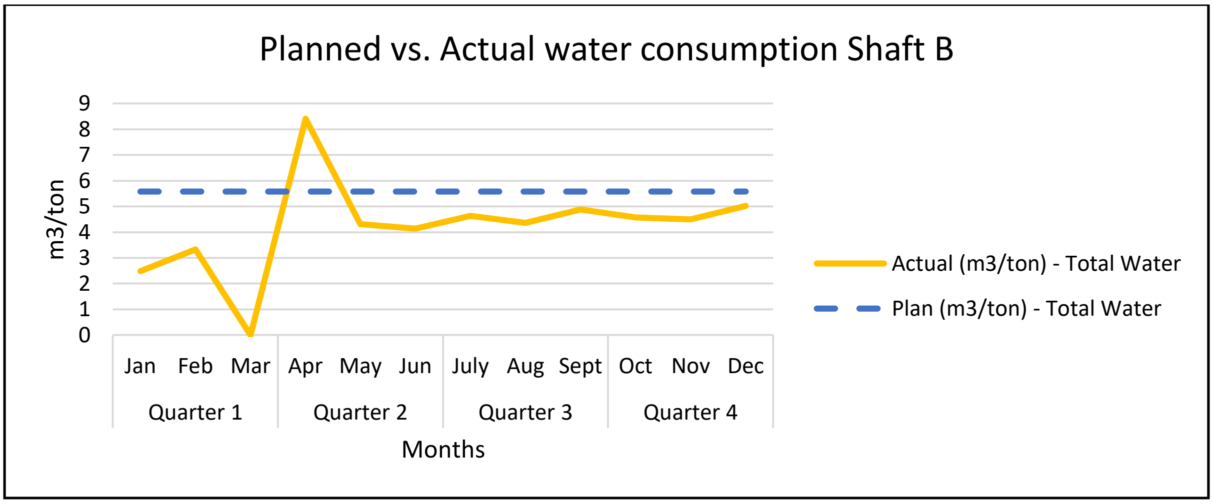

Figure 28 – Planned versus actual water consumption of Shaft B

Figure 28 shows Shaft B performs well when considering that it consumed 16.1% less water on average than that was planned for the specific year. B# does not use chilled water for mining purposes, it uses fissure water. This means that only pumping energy can be reduced when investigating a water reduction initiative and no refrigeration savings should be included in the calculations. The results of the calculations for Shaft B does not mean that the shaft is not able to reduce its water consumption even further to save on pumping energy, it simply means that it performed better than planned.

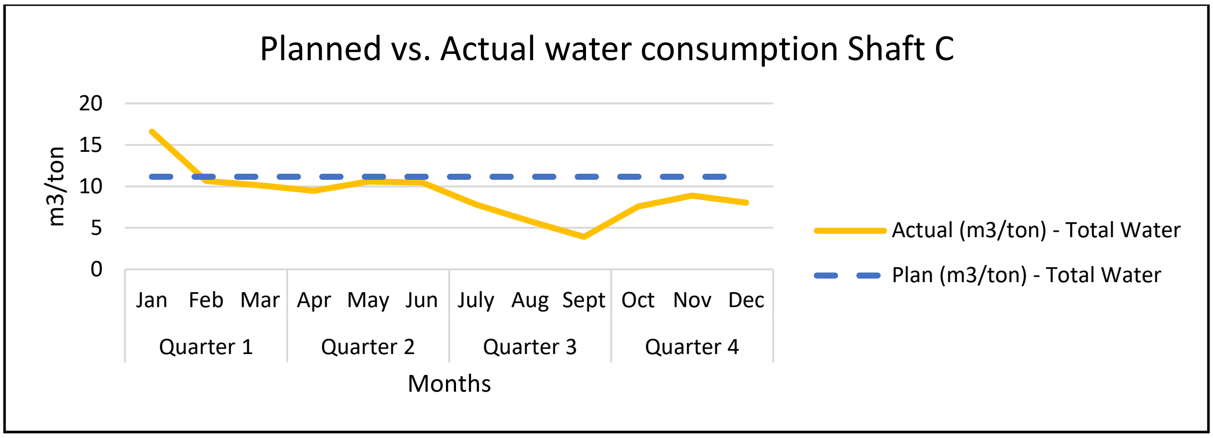

Figure 29 – Planned versus actual water consumption of Shaft C

Shaft C also performed well as can be seen in Figure 29. Shaft C consumed on average 18.1 % less water than what was planned for during the specific year that the data was provided. Similar to Shaft B, the results of the calculations for Shaft C does not mean that the shaft is not able to reduce the chilled water consumption, it simply means that it performed better than planned.

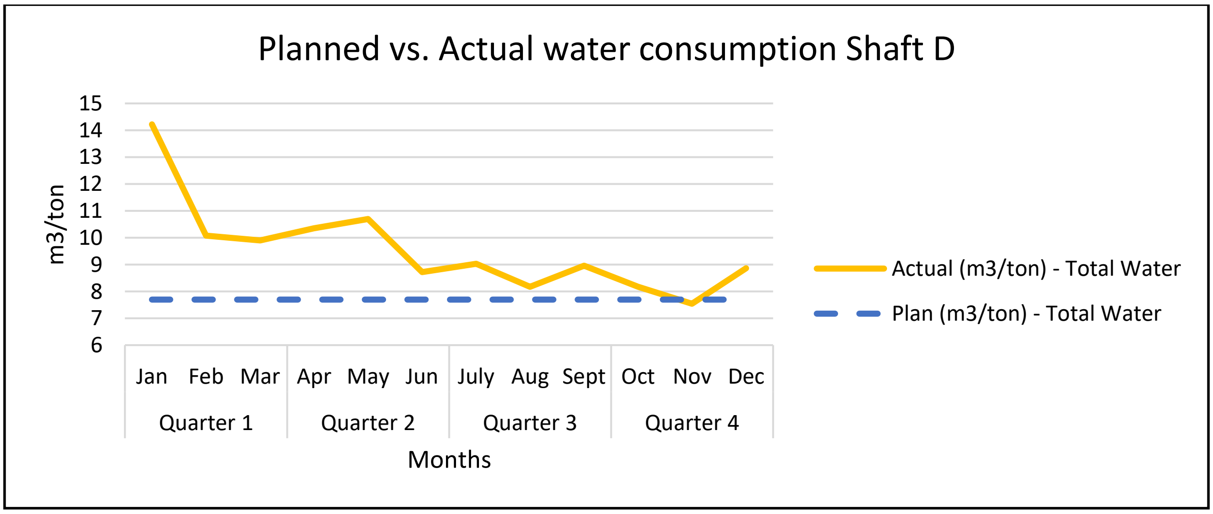

Figure 30 – Planned versus actual water consumption of Shaft D

Figure 30 shows that shaft D consumed more water than what was planned. This result implies that Shaft D poses an opportunity to reduce the chilled water that the shaft consumes. The fact that the shaft underperformed by 24.2 % leads to the conclusion that various areas of wastage exist.

To better understand the layout and how the systems integrate with each other, the following two figures will illustrate the general arrangements of Shaft A and Shaft D of the specific mine.

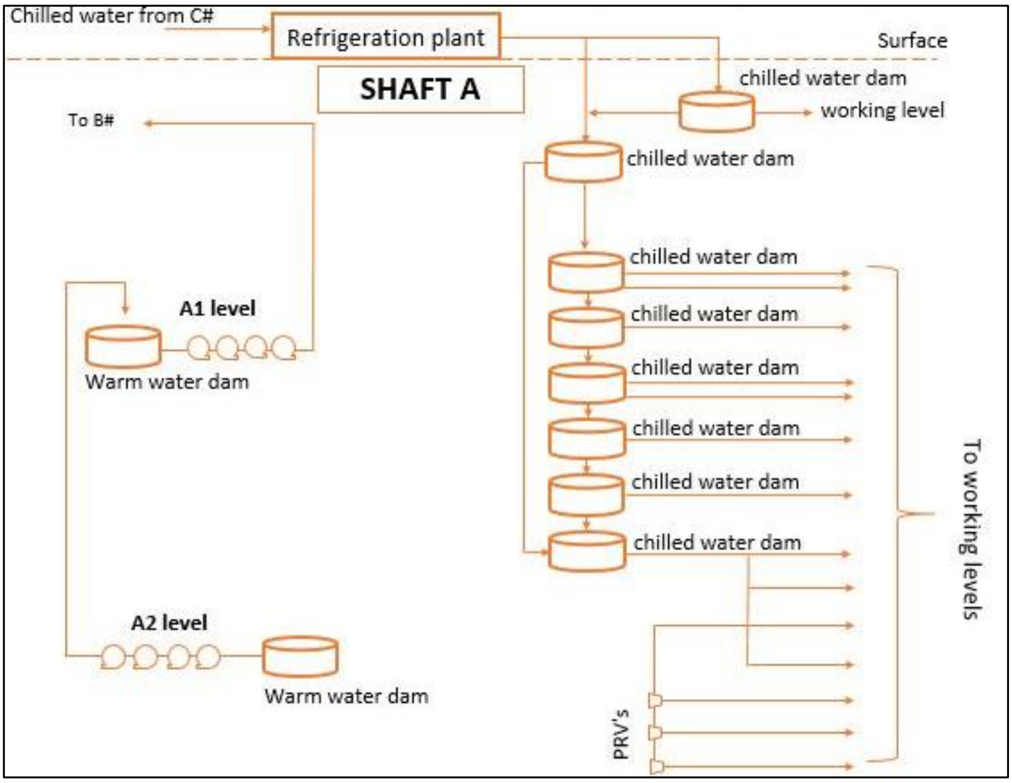

Figure 31 – Chilled water supply and dewatering layout of Shaft A

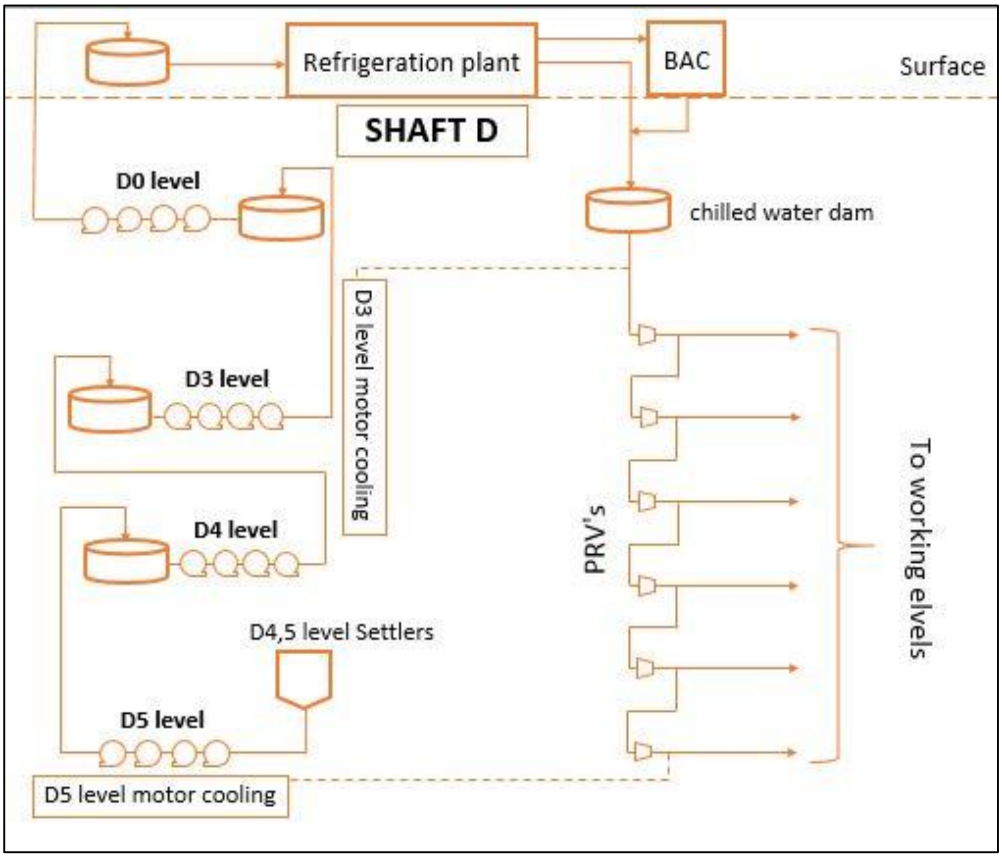

Figure 32 – Chilled water supply and dewatering layout of Shaft D

To compare the performance of this specific mine and the 4 shafts under investigation against the 2.6 m^3 per ton that Vosloo (Vosloo; 2008: 52) calculated, Table 2 was compiled.

Table 2 –Comparison of the actual water consumption against the benchmark (Vosloo; 2008: 52)

Shaft	Actual (m^3/ton)	Benchmark (m^3/ton)	Performance	Percentage (%)
A	12.0	2.6	+ 9.4	- 78.3
B	4.62	2.6	+ 2.02	- 43.7
C	9.16	2.6	+ 6.56	- 71.6
D	9.56	2.6	+ 6.96	- 72.8

The “+” in the “Performance” column indicates that the actual water usage is more than the benchmark that Vosloo (2008) set. The “-“ in the “Percentage” column indicates that the specific shafts are underperforming according to the benchmark as well (Vosloo, 2008: 52). The figure as stated by Vosloo is only an indicator of how well the mine under investigation was performing compared to an average calculated over various different mines and it will not be useful to discuss the details of the figure itself.

It is concluded that Shaft A and Shaft D have more potential to reduce the chilled water consumption than Shaft B and Shaft C, and therefore this study will further on only focus on them. Shaft C and D are overall performing close to one another. Shaft C has been ignored going forward as the focus of this study was on pump motor cooling and Shaft C did not have an opportunity to reduce the chilled water consumed for motor cooling. To reduce the amount of pumping and refrigeration that is required by Shaft A and D, three interventions have been identified that will be discussed in the following section.

3.3 Identified Interventions

As mentioned in the previous chapter, the pump motor cooling consumes a significant amount of chilled water. Depending on the type and size of the motor, the rate of chilled water consumption will vary. A site survey was conducted on the shafts under investigation and their respective pump types and sizes and a resultant magnitude of cooling water used per pump have been obtained.

Shaft A has two pumping stations with six pumps each and Shaft D has four pumping stations with six, six, eight and eight pumps respectively. This information indicates that a significant amount of chilled water can potentially be saved in terms of the pump motor cooling which will result in an electricity cost saving for the mine.

Three interventions have been identified to reduce the chilled water consumption by the pump motor coolers and will be discussed in more details in the chapters to follow.

In the chapters to follow the three different chilled water reduction initiatives will be separately discussed, including the Methodology, Case studies, Results, Verification and Validation.

- Chapter 4 – Energy saving initiative 1: Conversion to air cooling.

The cooling method was changed to totally eliminate the amount of chilled water that was being used at the specific pump station. Air cooling was fitted.

- Chapter 5 – Energy saving initiative 2: Booster pump station.

When the clear water from the dam at a pumping station is suitably clean and below 30℃, the clear water can be utilized for motor cooling. A booster pump station is necessary to boost the pressure from the dam and to overcome the pressure in the suction column where the coolers discharges. This intervention reduces the amount of chilled water used for motor cooling.

- Chapter 6 – Energy saving initiative 3: Implementing automated solenoid valves.

Automatic solenoid valves was implemented to close the chilled water supply used for motor cooling when a motor is not operational. The mine does not close the valves manually and this brings about chilled water being dumped and it has a significant cost impact.

The three interventions will be discussed in detail in the following chapters.

CHAPTER 4: CONVERSION TO AIR COOLING AT D# D3L

4.1 Background

At the case study mine, Shaft D, there is a pumping chamber located at D3 level named Site #1. Each pump was fitted with a conventional crossflow water-to-air motor cooler which cooled the electric motor's windings and bearings. The chilled water used for the motor cooling was discharged at a slightly higher temperature onto the footwall from where it flowed to the drain as illustrated in Figure 33, and eventually ending up in the hot water dam on a lower level.

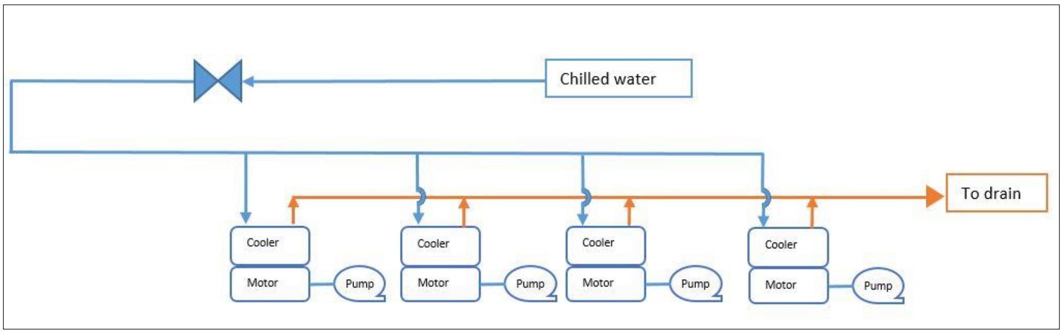

Figure 33 – Water cooled arrangement

Converting the pump motor cooling to an air source consists of removing the traditional water cooled crossflow heat exchanger on top of the motor, and fitting an open circuit air-to-air cooler. The existing feed of chilled water to the pump motor coolers can be blanked off completely as can be seen in Figure 34 switching over to air coolers can pose a set of new challenges if incorrectly implemented and some factors need to be consider.

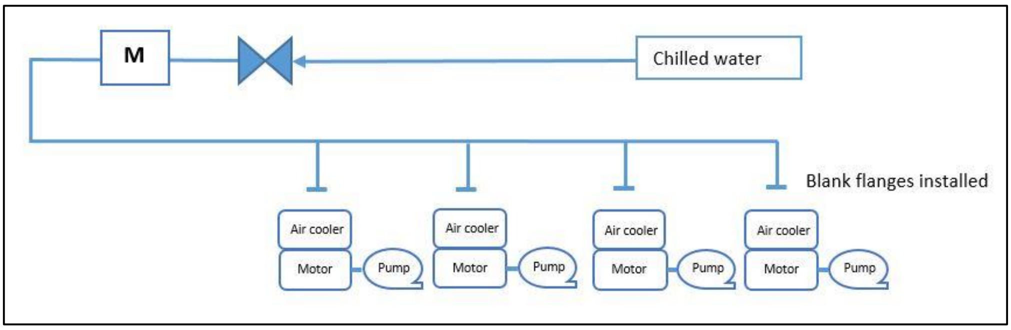

Figure 34 – Air cooled arrangement

The air cooler design is an open circuit design based on a once through configuration which divides the incoming and outgoing airways. Air is drawn in from the surroundings, routed through the inside of the motor over the windings and discharged, (Siemens AG, 2007) as indicated by Figure 35.

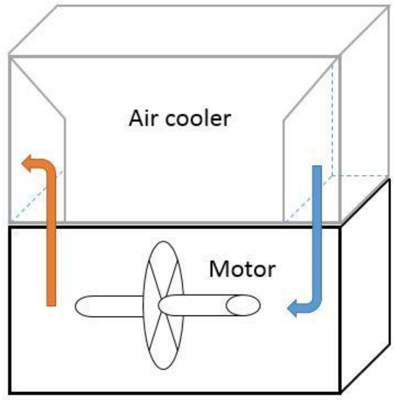

Figure 35 – Once through configuration air cooler

The air is drawn into the motor using an internal fan which rotates along with the shaft of the motor. Warmer air is then discharged from the motor and back into the ventilation stream. The design of the air cooler was altered based on a request from the mine moving from the first generation design to a second generation design. The second generation cooler has a diverter fitted which exhausted the outlet air at an angle to avoid blowing hot air into the next air cooler's intake as the pumps are positioned in a straight line configuration. The design was updated to a third generation after a concern was raised by the pump station foreman who was considering the possibility of water ingress in the motors. The following three figures, illustrate the changes made.

Figure 36 - First generation air cooler

Figure 37 – Second generation air cooler

Figure 38 – Third generation air cooler

4.2 Methodology

"Putting effective water metering technologies or methods in place and having an accurate site water model is critical" (DWAF, 2006). To measure the reduction of chilled water flow and to quantify the electrical savings, a flowmeter was installed on the chilled water supply line prior to the air cooler installation. To ensure the accuracy and reliable measurements from the flowmeter, a 100NB Magnetic flowmeter from Endress & Hauser was used (reference). The savings can be calculated as follows:

$$kW\ saved = Calculated\,\frac{kW}{\frac{l}{s}} \times \frac{l}{s}\,flow\ reduction \qquad [3]$$

The calculated kW per l/s value is site-specific and will only be applicable for this specific pump station as the location, depth and impact on refrigeration differ from other pump stations. Table 3 was developed to simplify the savings calculations and to provide a tool to calculate the kW/l/s value in less time with adequate accuracy. Parameters including the motor capacities, pump effectiveness, total vertical distance that needs to be pumped, friction losses, refrigeration capacity, condenser tower pumps, evaporator pumps, fans and compressor motors have been included in calculating a kWh/ML pumped value which transposes to the kW per l/s value used to calculate the savings.

Table 3 – kW per l/s for site-specific calculations

Shaft	Level	kW / l/s
A#	A2	12,06
	A1	7,82
	Fridge Plant	10,59
B#	B1	0,22
C#	C3	9,93
	C2	12,93
	C1	14,20
	Fridge Plant	16,48
D#	D5	6,74
	D4	13,35
	D3	14,01
	D0	13,12
	Fridge Plant	16,81

The air coolers were installed at D# D3 Level, meaning that the calculation will be done as follows:

$$D\#\ D3\ Level\ Total\ \left(\frac{kW}{\frac{litre}{second}}\right) = 16.81\ (Refrigeration) + 13.12\ (D0) + 14.01\ (D3\ Level) \qquad [4]$$

The calculation includes the refrigeration element because the water needs to be refrigerated on the surface and sent back down underground for re-use again. All pumps and refrigeration machines rated power on the surface were included in the calculation of the refrigeration element of the main calculation. The other two elements in the calculation account for the two pumping stations that the cooling water from the D3 level motor coolers would have passed through.

4.3 Results

At the time of installation, there were only 5 pumps operational on D3 level, as the sixth was removed for maintenance. The baseline will thus only account for the chilled water usage of 5 motor coolers. No assumptions or extrapolations were made to include the flow of the sixth motor cooler due to the fact that it has been taken out for repairs more than 18 months prior to the study and still has not been completed and returned.

The baseline in Figure 39 indicates that an average of 25.83 l/s of chilled water were used for the 5 motor coolers on D3 level. As described previously in this chapter, the focus of the air cooling intervention was to totally nullify the use of chilled water, as shown below.

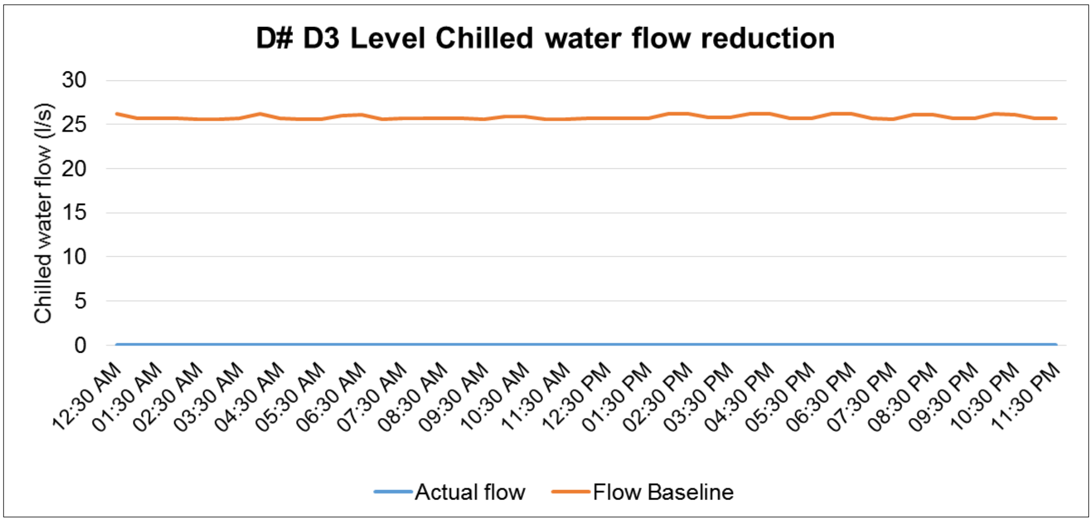

Figure 39 – D# D3 Baseline vs. Current flow comparison

Figure 39 verifies that indeed 25.83 l/s of chilled water flow has been reduced. Taking into account that at the specific site the calculated kW per l/s value was 43.94 kW/l/s, it calculates to an electrical saving of 1134 kW. The energy savings is fairly constant during weekdays and even on Saturdays and Sundays due to the constant water flow that was always present during the baseline period.

Changing the method of cooling raises a concern as to whether the electrical motor will operate at the same conditions as it did with the closed loop chilled water coolers. The mine monitors the motor's temperature at critical points of certain pumps per pump station. Of the 5 operational motors present in the pumping station, only two motors are equipped with sensors. The two motors that do have data to monitor are located in the middle of the inline configuration and next to each other, which makes it acceptable to assume that the other motors will perform similar to these two, if not better.

To compare the technical performance of an electrical motor with the two different cooling methods, a baseline was calculated with data from when the chilled water heat exchanger was still used. Then thereafter the performance of the air coolers was monitored, with the motor winding temperature and the motor bearing temperature being the critical parameters. Table 4 shows the temperature sensors found in a typical motor at the case study mine.

Table 4 – Temperature sensors

Temperature sensor number:	Description
1	DE Bearing Temperature
2	Motor Winding Temperature 1
3	Motor Winding Temperature 2
4	Motor Winding Temperature 3
5	NDE Bearing Temperature
6	Air Temperature

Figure 40 show a sample of the temperatures measured for the two pumps.

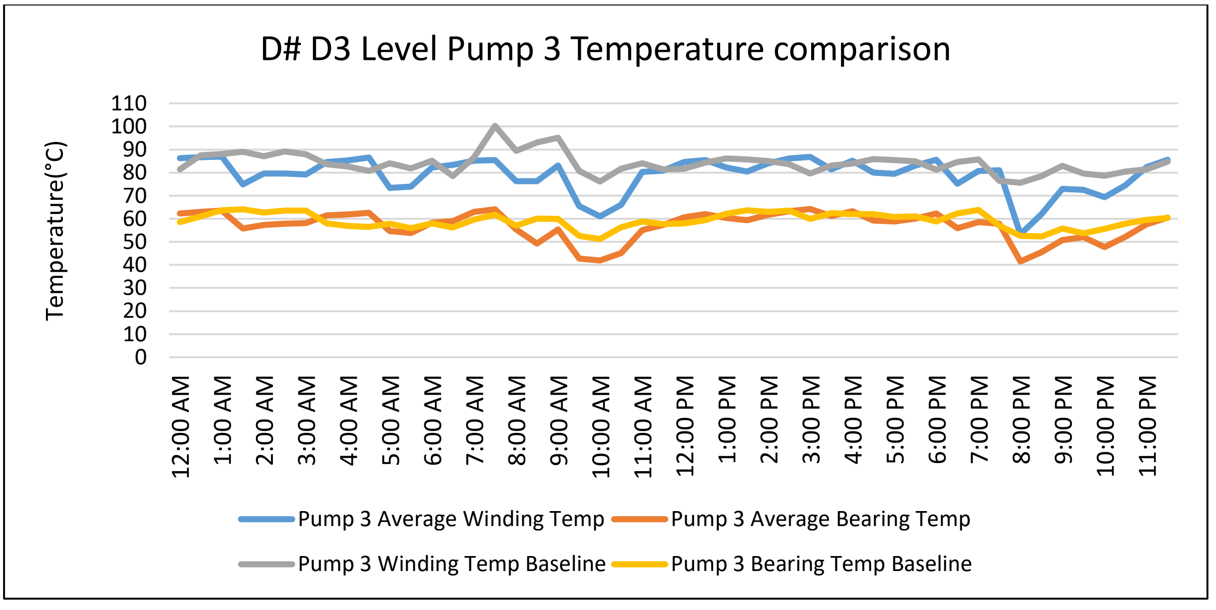

Figure 40 – Pump 3 Temperature comparison

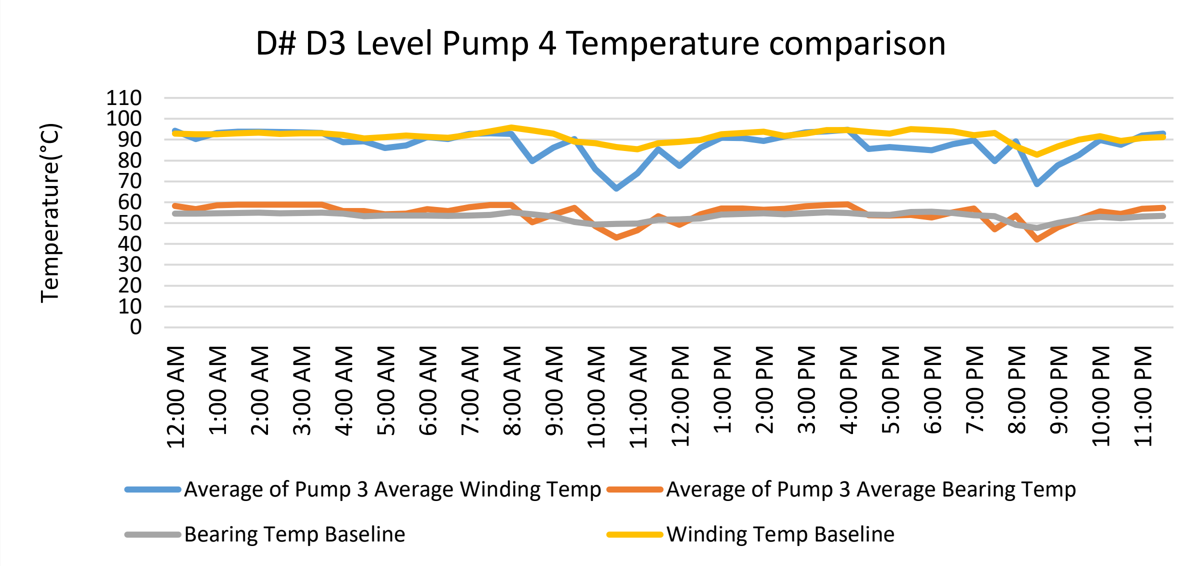

Figure 41 – Pump 4 Temperature comparison

The average winding temperature of the two motors was 7% warmer than the baseline, with the average bearing temperatures 5% lower than the baseline. The air coolers therefore performs satisfactory and within the temperature trip limits of the motors. The small change in operating temperatures will not result in a noteworthy change in motor power consumption in comparison to the amount of energy and financial savings realized by the initiative. For further temperature and initiative performance graphs refer to Appendix – A.

Not all pump stations are suited for the conversion to air cooling as the ambient temperature, humidity and ventilation layout need to be considered before a modification is implemented. The ventilation arrangement of the pump station needs to be of such nature that the outlet side of the pump station is open ended into an up-cast column. An up-cast column transports the ventilation air out of the mine and therefore the heat that has been added exits the mine immediately. It will therefore have no impact on the energy that is used by the BAC to cool down the ventilation air that is sent down the mine. If the ventilation outlet of the pump station dumps into a down-cast column, the heat energy that is added to the ventilation needs to be taken into account on the overall energy balance.

At Shaft D, D3 level, the ventilation unfortunately dumps into a down-cast which enters the sub-shaft and flows to the bottom levels and working sections of the mine. When the ventilation air have passed through all the relevant areas, it returns through the return airway (RAW). The RAW directs the ventilation air upward to D4 level where the underground refrigeration plant is located. The ventilation air exits the mine through the condenser cooling tower and the extraction fans.

Due to the ventilation of a mine being an incredibly complex network of end-users it is a time consuming and high-level calculation process that needs to be followed to calculate the impact of the air coolers on the ventilation temperature of the mine at each relevant area. That is not the focus of this study, however ventilation surveys were done on the relevant levels to obtain knowledge and evidence of the effect that the air coolers had on the ventilation system of the shaft. This was done to determine whether the air coolers are an effective solution and did not increase the cost of ventilation and refrigeration. The ventilation is supplied down the main shaft, then it divides into three levels as indicated in Figure 42, namely D1, D2 and D3 level.

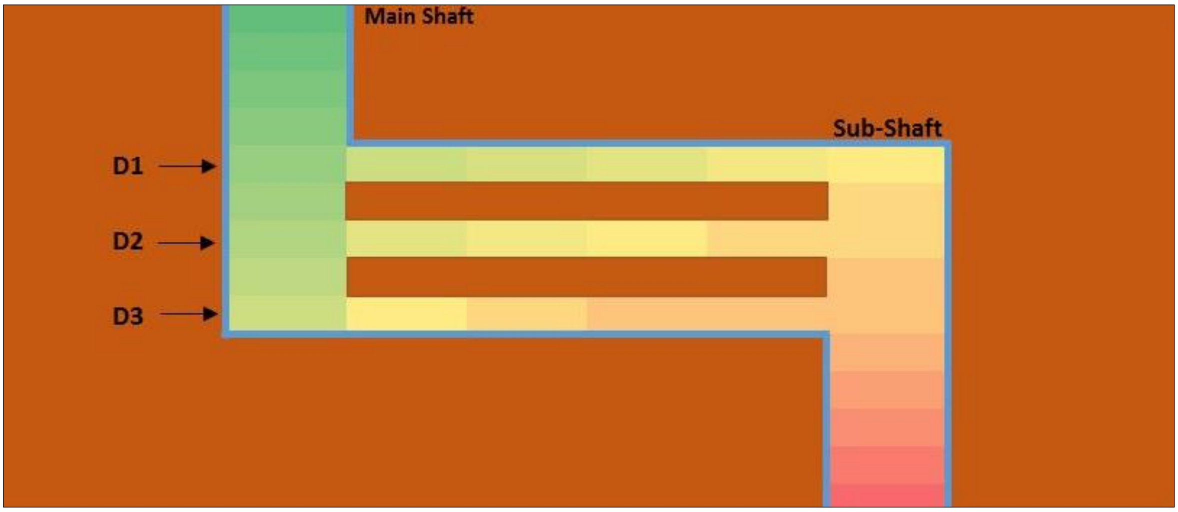

Figure 42 – Ventilation network on D1, D2 and D3 level

In Table 5 the activities and descriptions of each level are given:

Table 5 – D1, D2 and D3 level descriptions

Level	Description
D1	Turbine and sub-shaft headgear level
D2	Haulage
D3	Pump station

The main shaft supplies each level with ventilation air and exits into the sub-shaft, which flows down and feeds the rest of the mine. Temperature and flow rate measurements were taken after commissioning of the project at the entrance to each level, and due to the mine configuration, the measurements for the three levels were expected to be close to each other due to the only factor impacting the temperature being the VRT that will increase with depth. The same tests were repeated at the exit of each level into the sub-shaft. The temperature and flow rate results are summarized in the following table:

Table 6 – Environmental test results on D1, D2 and D3 level

Level	T_{wb} in (℃)	T_{wb} out (℃)	T_{db} in (℃)	T_{db} out (℃)	Volume flow rate in (m^3/s)	Volume flow rate out (m^3/s)
D1	21.7	22.0	30.9	29.3	77.5	67.5
D2	21.9	22.3	31.9	29.8	87.5	75
D3	21.9	22.2	32.4	33.3	160.0	200.0

Because the main ventilation supply of the shaft splits through three levels and joins again afterwards to flow down to the mine workings, a temperature rise of less than 5% on one of the levels will not impact the sub-shaft temperature significantly. The horizontal length of the three levels is assumed to be equal between the main shaft and sub-shaft due to the positions thereof.

The results of the environmental test can be judged as reliable and accurate due to the quality of the equipment used as well as the experimental procedures followed. The test results are also significant due to three pump motors with air coolers being operational at the time of the test and two split casing pumps were also operational which adds additional heat.

Figure 43 shows a simple mass flow balance model forecasting the combined discharge temperature of the three streams.

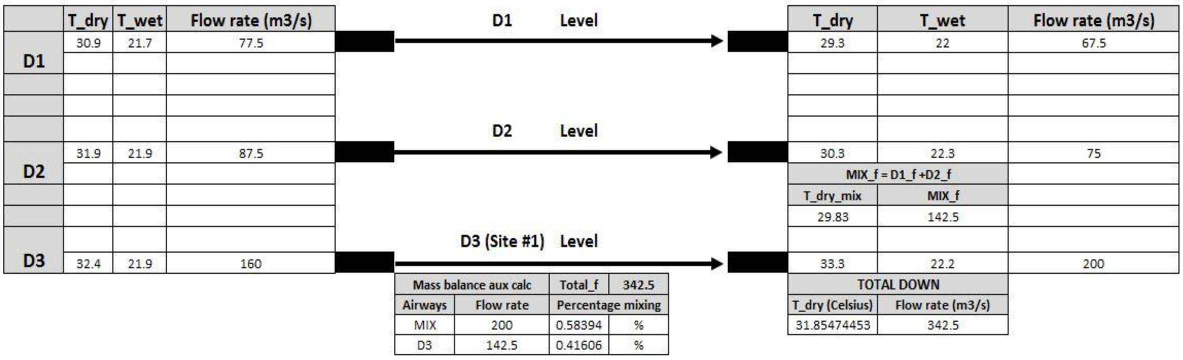

Figure 43 – Ventilation model of the location of the air coolers

The model verifies that the air coolers did not impact the temperature of the ventilation downstream significantly. The model forecasted that a 1.6% temperature increase can be expected. The temperature rise over the D3 level pumping station is negligible when compared to the excessive amount of power and cost savings realised by the initiative.

When calculating the financial impact of an electricity saving initiative, it is important to state in which time of the day the initiative have realised the savings. To simplify the calculations a daily average price has been calculated as listed in Table 7.

Table 7 – Calculation of average price tariffs

	TARIFFS (c/kWh)					
	Winter			Summer		
	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday
00:00	49,4	49,4	49,4	43,99	43,99	43,99
00:30	49,4	49,4	49,4	43,99	43,99	43,99
01:00	49,4	49,4	49,4	43,99	43,99	43,99
01:30	49,4	49,4	49,4	43,99	43,99	43,99
02:00	49,4	49,4	49,4	43,99	43,99	43,99
02:30	49,4	49,4	49,4	43,99	43,99	43,99
03:00	49,4	49,4	49,4	43,99	43,99	43,99
03:30	49,4	49,4	49,4	43,99	43,99	43,99
04:00	49,4	49,4	49,4	43,99	43,99	43,99
04:30	49,4	49,4	49,4	43,99	43,99	43,99
05:00	83,32	49,4	49,4	43,99	43,99	43,99
05:30	83,32	49,4	49,4	43,99	43,99	43,99
06:00	254,12	83,32	49,4	64,11	43,99	43,99
06:30	254,12	83,32	49,4	64,11	43,99	43,99
07:00	254,12	83,32	49,4	89,02	64,11	43,99
07:30	254,12	83,32	49,4	89,02	64,11	43,99
08:00	254,12	83,32	49,4	89,02	64,11	43,99
08:30	254,12	83,32	49,4	89,02	64,11	43,99
09:00	83,32	49,4	49,4	89,02	64,11	43,99
09:30	83,32	49,4	49,4	89,02	64,11	43,99
10:00	83,32	49,4	49,4	64,11	43,99	43,99
10:30	83,32	49,4	49,4	64,11	43,99	43,99
11:00	83,32	49,4	49,4	64,11	43,99	43,99
11:30	83,32	49,4	49,4	64,11	43,99	43,99
12:00	83,32	49,4	49,4	64,11	43,99	43,99
12:30	83,32	49,4	49,4	64,11	43,99	43,99
13:00	83,32	49,4	49,4	64,11	43,99	43,99
13:30	83,32	49,4	49,4	64,11	43,99	43,99
14:00	83,32	49,4	49,4	64,11	43,99	43,99
14:30	83,32	49,4	49,4	64,11	43,99	43,99
15:00	83,32	49,4	49,4	64,11	43,99	43,99
15:30	83,32	49,4	49,4	64,11	43,99	43,99
16:00	83,32	49,4	49,4	64,11	43,99	43,99
16:30	83,32	49,4	49,4	64,11	43,99	43,99
17:00	254,12	83,32	49,4	64,11	43,99	43,99
17:30	254,12	83,32	49,4	64,11	43,99	43,99
18:00	254,12	83,32	49,4	89,02	64,11	43,99
18:30	254,12	83,32	49,4	89,02	64,11	43,99
19:00	83,32	49,4	49,4	89,02	64,11	43,99
19:30	83,32	49,4	49,4	89,02	64,11	43,99
20:00	83,32	49,4	49,4	64,11	43,99	43,99
20:30	83,32	49,4	49,4	64,11	43,99	43,99
21:00	49,4	49,4	49,4	64,11	43,99	43,99
21:30	49,4	49,4	49,4	64,11	43,99	43,99
22:00	49,4	49,4	49,4	43,99	43,99	43,99
22:30	49,4	49,4	49,4	43,99	43,99	43,99
23:00	49,4	49,4	49,4	43,99	43,99	43,99
23:30	49,4	49,4	49,4	43,99	43,99	43,99
	AVERAGES (c/kWh)					
	107,60	56,47	49,40	62,59	48,18	43,99

In Table 7 it can be seen that the times for the respective tariff is different when comparing summer against winter. During winter, the whole tariff structure also shifts one hour earlier than the summer structure. This is done to compensate for the national demand peak being earlier in winter than in summer. Table 8 summarizes the average electricity cost per unit of electricity used:

Table 8 – Average electricity cost summary

Average Electricity Cost	c/kWh
Winter	
Weekday	107,6
Saturday	56,47
Sunday	49,40
Summer	
Weekday	62,59
Saturday	48,18
Sunday	43,99

Table 9 describes how the financial calculation has been conducted from kW saved to Rand saved, using the following equation:

$$Daily\ Financial\ Savings = kW\ saved\ \times 24\ hours\ \times Cost\ per\ kWh \qquad [5]$$

Table 9 – Air cooler savings cost calculation

DAILY SAVINGS = 1134kW			
WINTER	**Calculation**	**SUMMER**	**Calculation**
Weekday	1134kW x 24h x (107.6/100)	**Weekday**	1134kW x 24h x (62.59/100)
Saturday	1134kW x 24h x (56.47/100)	**Saturday**	1134kW x 24h x (48.18/100)
Sunday	1134kW x 24h x (49.4/100)	**Sunday**	1134kW x 24h x (43.99/100)

Table 10 – Air cooler financial savings results

DAILY SAVINGS = 1134kW			
WINTER	**Financial Saving**	**SUMMER**	**Financial Saving**
Weekday	R 29 300	**Weekday**	R 17 000
Saturday	R 15 000	**Saturday**	R 13 100
Sunday	R 13 400	**Sunday**	R 12 000

Table 10 summarises the results of the financial savings for the different days and tariffs that must be taken into account. The total annual electricity savings can be calculated as follows:

$$D\#\ D3\ Level\ Annual\ Electricity\ Savings = Total\ MW\ saved\ \times 24h\ \times 365days \quad [6]$$

$$D\#\ D3\ Level\ Annual\ Electricity\ Savings = 1.134\ MW\ \times 24h\ \times 365days$$

$$D\#\ D3\ Level\ Annual\ Electricity\ Savings = 9\ 934\ MWh$$

This significant amount of electricity savings that the air coolers realised, also impacts the financial savings of the mine. The total annual operational cost saved based on the rates and structures mentioned in this dissertation accumulates to a significant amount of R 5.7 million. It is therefore shown that reducing the chilled water consumption at D# D3L by implementing air coolers instead of closed loop water coolers on the pump motors, does have a significant positive impact on the electricity usage and financially benefit the mine.

CHAPTER 5: BOOSTER PUMP STATION ON A# A2 LEVEL

5.1 Background

Before the intervention was implemented chilled water was sent from A1.1 level through a 150mm nominal bore (NB) shaft column to A1.2 level and further towards A2 level. On A1.2 level chilled water was supplied through a 50NB valve for dozing purposes. This was a manual system and it was found that the water feed ran continuously to pre-mix chemicals before entering the settlers on A1.2 level.

The balance of the A1.1 level cold water feed was used on the A2 level. This water was mainly used for pump motor cooling (94%), mud pump flushing (3%) and general washing (3%). The cold water feed to A2 level was also controlled manually as well as the flow to all the processes. All chilled water consumed on A2 level was then discharged to the drain from where a sump pump was used to pump the water back to the clear water dams on A1.2 level.

Due to the low-pressure specification of the cooling water piping system on A2 level, the operators were forced to leave some of the motor cooling valves open to avoid excessive pressure damage to the A2 level chilled water piping and pump motor coolers. The system is shown in Figure 44.

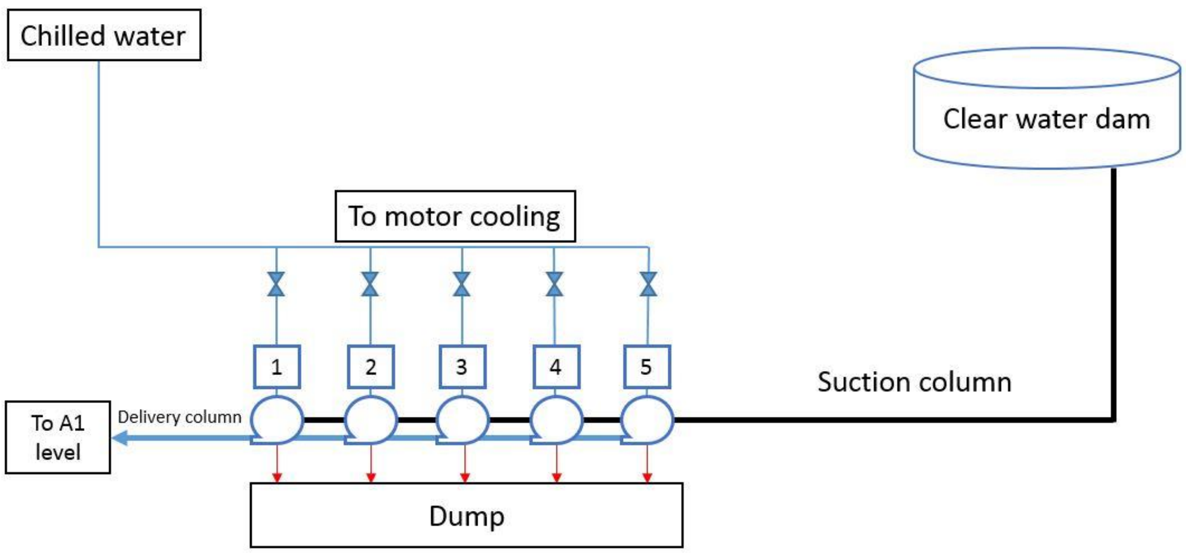

Figure 44 – Old motor cooling system

The new motor cooling water system as implemented by this study stopped using the flow of chilled water from A1.1 level down to A1.2 level and A2 level. On A2 level the motor cooling piping arrangement has been changed to cool the motors with water from the clear water dams. The temperature of the clear water is sufficiently low enough to cool the motors as the motor specification from the Original Equipment Manufacturer (OEM) stipulates that it should be below 30℃. The pH of the water was tested and found to be 7.3 where the required range was 7 to 8.5. The total alkalinity as $CaCO_3$ was 60mg/l and the required range is 60-100mg/l. The total suspended solids of the clear water was found to be 25 parts per million (ppm). This results were accepted as satisfactory conditions for use in motor cooling.

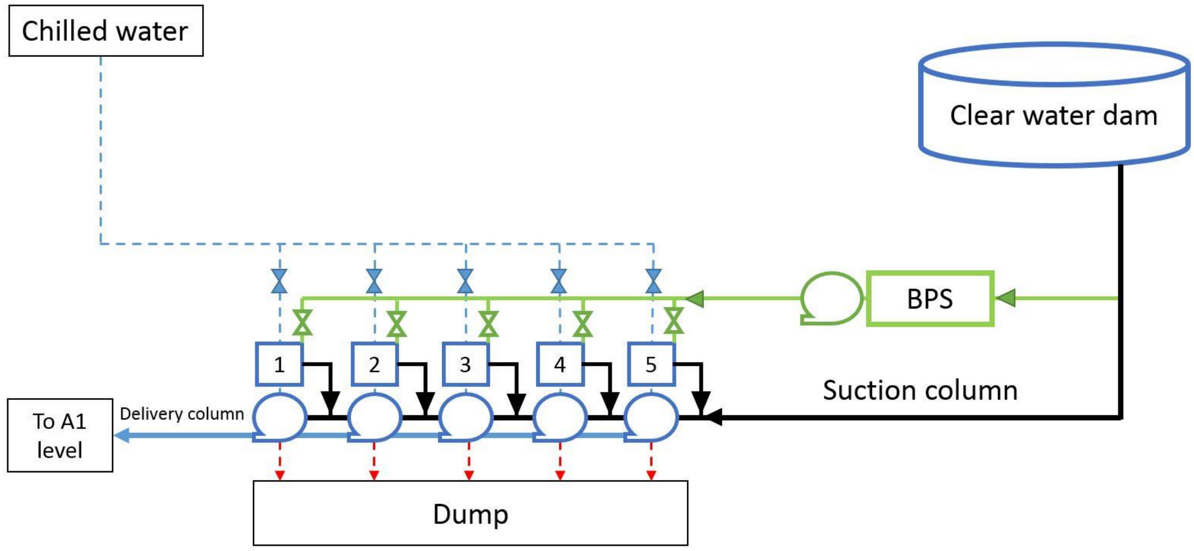

Figure 45 – New motor cooling system

A booster pump system has been installed to boost the pressure in the system to 5 bar to overcome the pressure of maximum 4 bar that is already in the suction pipe. The pressure in the suction pipe varies a small amount due to the head of the dam. The clear water is pumped through the motor coolers and discharged back into the 1100NB suction column. The booster pumps also supply the mud pumps and any open hoses for general washing purposes after which the water will still be discharged into the drain system. The existing sump pump will then pump the drain water back to the clear water dams on A1.2 level. Refer to Appendix B2 for the Piping and Instrumentation Diagram (P&ID) for more details about the layout.

The booster pump system suction has been connected to the 1100NB clear water dam suction line, with the discharge from the booster pump system connected to the existing cooling water feed line, originally from the chilled water feed line. The suction line and discharge lines of the booster pump system have been interconnected to allow water flow to the clear water pumps, mud pumps and washing when the booster pumps are not running. The interconnected line also supplies sufficient water flow to the mud pumps and washing when the booster pumps are not running.

A new 100NB common receiving pipeline has been installed to route all the outlet motor cooling water back to the 1100NB clear water pump suction line. A 100NB dump line and an actuated isolation valve have been installed between the common receiving line and the drain. This dump line opens when the clear water pump motors need to be cooled when the booster pump station is out of service. A new sand filter has been installed on the downstream side of the interconnection line to provide additional water cleaning for further protection of the motor cooler tubes.

The option to re-introduce the cooling water supply from A1.1 level will always be available as shown by dotted lines in Figure 45. This option will introduce water pressure up to 70 bar on the motor coolers and piping. To reduce the possibility of over pressurising the motor coolers and water lines a pressure relief valve has been installed in the existing 100NB motor cooler water feed line.

The chilled water feed from the shaft is isolated at the station on A2 level. The A1.1 level chilled water feed line down to A1.2 and A2 level are also isolated on A1.1 level, thus the original chilled water feed to A1.2 and A2 levels are replaced by clear water.

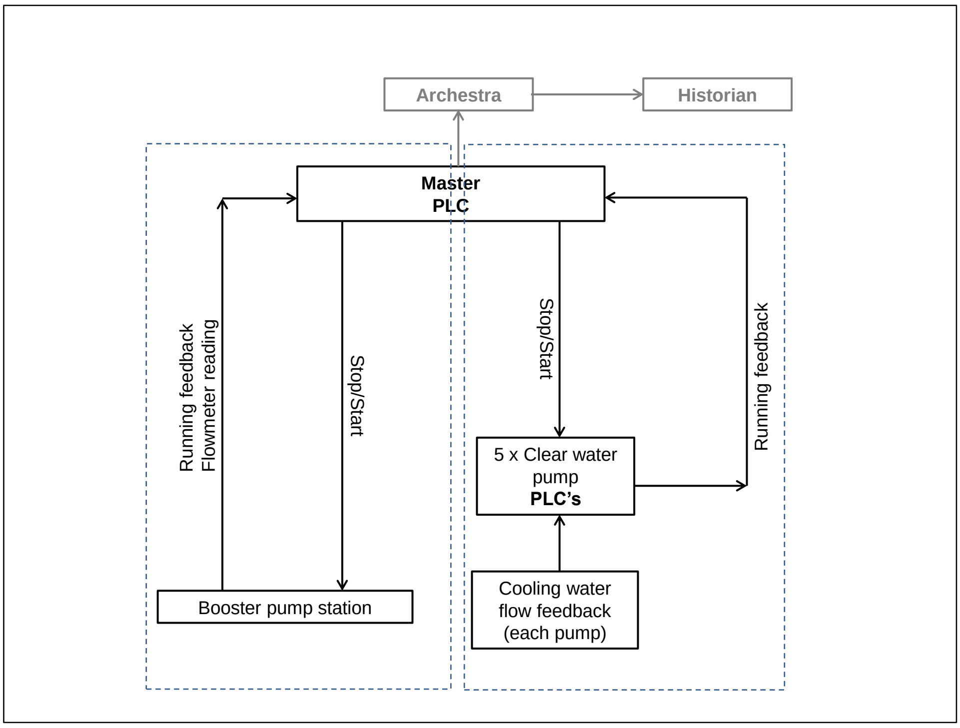

Figure 46 – Context diagram of the control

Two different control loops are required to incorporate the automatic pump control that the specific pump station operates under. The Master PLC controls the stop and start function of the booster pumps which supply the required motor cooling flow for the clear water pump to be able to start. The Master PLC also controls the stop and start function of the clear water pumps based on the logic shown in Figure 46.

In the following two tables the specifications and the requirements of the motors and pumps are given:

Table 11 – A# A2 level motor cooling specifications

Motor type	Cooling water flow	Cooling water inlet temperature	Cooling water inlet pressure
WEG (2750 kW)	5 l/s	30 °C	6.25 Bar
ABB (2100 kW)	3 l/s	35 °C	6.25 Bar

Table 12 – A# A2 level mud pump and washing specifications

Description	Cooling water flow (per pump)	Cooling water inlet temperature	Cooling water inlet pressure
Mud pumps	0.5 l/s	Not applicable	Not applicable
Washing	2 l/s	Not applicable	2-5 bar

Based on this information the maximum working water flow rate required on A2 level is 8.5 l/s consisting of:

- One off 2750kW WEG motor, total 5 l/s

  OR

- Two off 2100kW ABB motors, 3l/s each total 6 l/s

  AND

- One mud pump, total 0.5 l/s (for two hours each shift)

  AND

- Washing: 2 l/s (sporadically)

A detailed flow simulation model was developed to calculate the water flow availability for motor cooling, the mud pumps and washing for all possible scenarios. The simulation can be found in Appendix B1 – Flow simulation.

5.2 Methodology of financial cost savings calculation

On the station at A1.1 level, an existing flowmeter was used to measure the chilled water flow sent down to A1.2 level and A2 level. This flowmeter provided data for three months prior to the installation of the booster pump station to serve as a baseline period. The data for the baseline period was used to calculate and plot a baseline graph and data set against which the chilled water savings could be measured.

Actual flow data of chilled water being sent down from A1.1 level were obtained and a calculation could be done to determine how much chilled water are being saved with the following equation:

$$A\#\ Chilled\ water\ flow\ reduced = A1.1L\ Baseline\ flow - A1.1L\ Actual\ flow \qquad [7]$$

The amount of kilowatts saved can then be calculated by using the reduction in chilled water flow as well as the kW per litre per second values as stipulated in Table 3. The same method that has been used in Equation 4 can now be applied to compile Equation 8.

$$A\#\ A2\ level\ total\ \left(\frac{kW}{\frac{litre}{second}}\right) = A2 + A1 + B1 + C2 + C1 + Fridge\ plant \qquad [8]$$

$$A\#\ A2\ level\ total\ \left(\frac{kW}{\frac{litre}{second}}\right) = 63.71$$

Equation 8 consists of six constant values each representing a pumping station or refrigeration plant. The dewatering cycle of A# interconnects with the pumping stations on B# and C# and by taking that into account the total amount of pumping power saved accumulates to a significant saving. The following table and figure describe the relevance and physical location of each term in the equation.

Table 13 – Equation 8 term description

Shaft	Level	kW/l/s
A#	A2	12.06
	A1	7.82
B#	B1	0.22
C#	C2	12.93
	C1	14.20
	Fridge plant	16.48

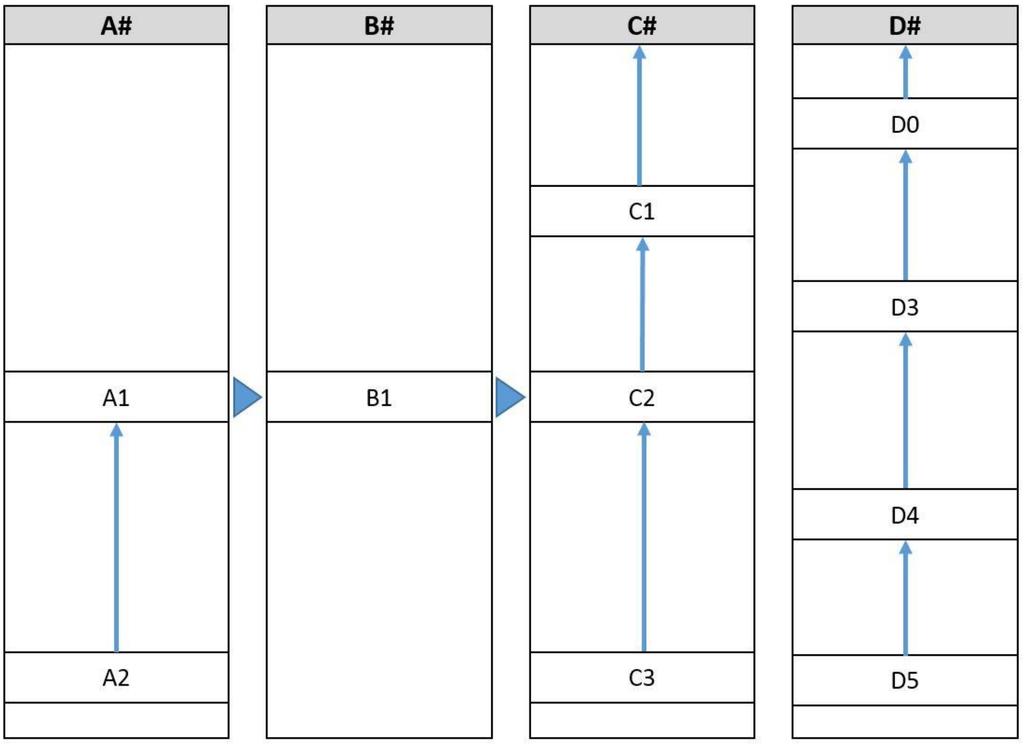

Figure 47 – Dewatering overview of the mine

As can be seen from Figure 47 the water from A# A2 level is pumped to A1 level. From A1 level the dewatering system interconnects with B# B1 level, which interconnects with C# C2 level. From C# C2 level the dewatering pumps pump the water to C1 level and from C1 level it is pumped to the surface dams from where the refrigeration plant receives its warm water supply from.

5.3 Results

The calculated average chilled water flow reduction is 10 l/s. Multiplying the amount of chilled water saved with the kW per l/s value associated with the water savings initiative will result in the amount of kW actually saved. Mathematically the additional power consumed by the booster pumps must be subtracted from the kW saved figure. However, the booster pump is not solely responsible for the savings. If the clear water dam is at a high enough level, the booster pump can remain non-operational and savings will still be realised due to the gravity feed from the dam. If the dam is at a high enough level, the pressure going through the motor coolers is sufficient and the dump valve will open to allow flow through the coolers. For this reason, the power consumed by the small booster pumps can't be subtracted constantly from the total amount of savings. The small booster pump is also Variable Speed Drive (VSD) controlled which implies that the power consumption differs over time, it will very seldom consume the nameplate rated power. Due to the large difference between power savings against power consumed, the mine agreed to neglect the power consumed by the small booster pumps.

The motor winding temperatures of the dewatering pumps were analysed to determine and verify whether the motors are operating within acceptable limits and to compare the performance against the motor winding temperature baseline which was calculated and plotted for the same period that the flow baseline was recorded.

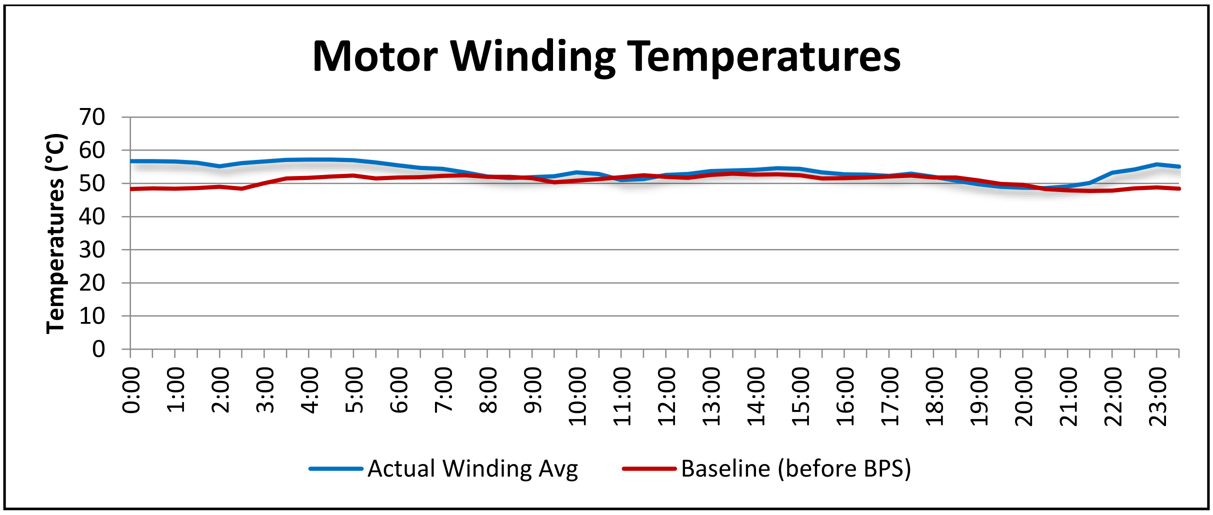

Figure 48 – Motor winding temperatures

The high-temperature trip set point is governed at 115℃ and the average operating temperature of motor windings in an underground environment is 70℃. From the motor winding temperature graph above it can be concluded that the motors are operating well within specification and the variation from the baseline can be regarded as negligible when compared to the amount of power and cost that the initiative is saving. The average operating bearing temperature in an underground environment is 60℃. The bearing temperature graph also shows that the motors are operating within specification.

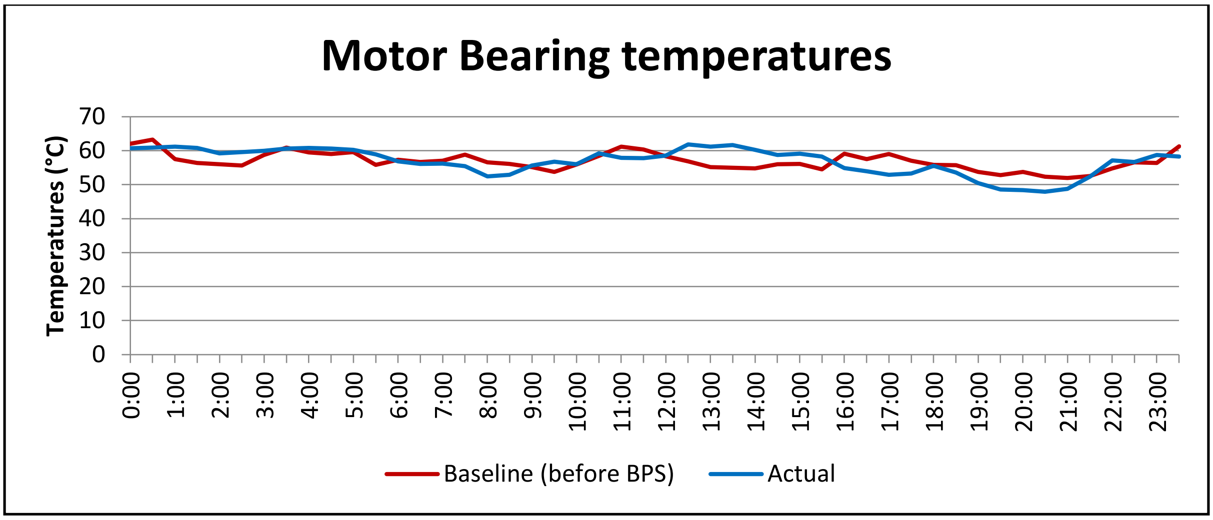

Figure 49 – Bearing temperature (NDE and DE)

The amount of kW saved can be used to calculate the financial savings due to this intervention. The same method of calculation which was used in the previous chapter can be used in this instance, with the same c/kWh values applicable as well as the seasons and different days. The average flow reduction from A1.1 level was 10 l/s. This calculated to an average kW saving of 700kW. This power saving proves that by reducing the amount of chilled water consumed by the pump motor coolers, the amount of power consumed can also be reduced. The booster pump station initiative realises a cost saving of R 3.6 million annually. For further temperature and initiative performance graphs refer to Appendix – B2.

CHAPTER 6: AUTOMATED SOLENOID VALVES D# D5 LEVEL

6.1 Background

Chilled water was supplied from D4.1 level through a 100NB shaft column to D5 level. This water is used for pump motor cooling, mud pump flushing and general washing on the level. The cold water pressure to D5 level is controlled by an adjustable pressure ratio valve at D4.1 level.

Each pump motor has a conventional water-to-air heat exchanger with a chilled water connection. Ambient air is drawn through the heat exchanger cooling the ambient air temperature down before it enters the motor by means of the motor's internal fan forcing the flow of the air. The water leaving the heat exchanger is dumped in the sump which is then pumped into steel tanks on D5 level with a small spindle pump. From here it is pumped to D4.1 level where it will enter the settlers to form part of the dewatering system. Each pump motor has a separate 25NB chilled water feed with a manual valve.

In the case of a loss in chilled water feed, the clear water from the suction line can be used as an alternative by manually opening the valve to the suction line which will cause clear water to rush into the chilled water line and through the heat exchangers into the sump.

Air coolers were also considered but due to the high humidity and higher temperature at D5 level it was eliminated as an option. The ventilation at D5 level is also poor and for that reason could not be a possibility as an alternative cooling method to realize cost savings. Refer to Figure 51 for a layout of the system mentioned above.

6.2 Existing control methodology

The start and stop sequencing of the clear water pumps on D5 level is an automated system consisting of a PLC that checks if the conditions of the pump and motor are within specifications before the pump can be started. One of the system checks is the availability of motor cooling water flow. A flow switch is used on D5 level to establish and monitor that there is sufficient water flow through the motor cooler.

6.2.1 Clear water pump start-up

The chilled water feed to each of the motor coolers is operated manually. The pump operator needs to open the motor cooling water valve to a specific pump to establish the necessary flow before the pump can start. The operator starts the pump by pressing the Start button on the existing pump control panels after which the PLC follows the standard pump start-up procedure which includes confirming the motor cooling water flow.

6.2.2 Clear water pump stop and pump trip

The pump operator stops the clear water pumps on D5 level by pressing the Stop button on the pump control panel. The pump operator closes the motor cooling water flow valve manually once the pump has stopped completely either by a controlled stop or a pump trip.

The manual operation of the cooling water valves is a major limitation in the system and chilled water wastage occurs at this point in the system. The pump operators are reluctant to open and close the valves manually. They rather leave it open on a permanent basis which means that they do not have to manually operate the valves, which is a “normal” occurrence in the underground environment. The human factor plays a huge role in the chilled water wastage. Some valves are also left open to protect the system against over pressure.

6.3 Automated valves control methodology

6.3.1 New arrangement: Mechanical layout

A bulk flowmeter complete with a logging system was first installed to establish the existing water usage. In order to minimise the excessive use of chilled water, a number of automated solenoid valves were then installed. These automated solenoid valves ensure that chilled water through a motor cooling system is only used when the motor is operational.

By closing the chilled water flow line a pressure build-up will be created in the system. Therefore an adjustable Pressure Reducing Valve (PRV) and a pressure relief valve were introduced into the system as an additional safety precaution. The PRV reduces the pressure from 2.0 MPa to less than 1.2 MPa. In a scenario where the PRV fails to reduce the pressure, the pressure relief valve will open at a pressure of 1.6 MPa blowing off into the sump protecting the 1.6 MPa system against over pressure.

The existing manual valves were not removed but adjusted to the required flow rate as per the specifications of the mine and the OEM’s. By throttling the water flow further additional water savings can be achieved, as long as the motor receives sufficient chilled water flow to reject the heat load.

6.3.2 New arrangement: Control and instrumentation

The solenoid valve installation was kept as simple as possible due to the mining environment it is used in. It was therefore only connected to the pump PLC to avoid unnecessary complexities. Figure 50 illustrates the control logic that was implemented.

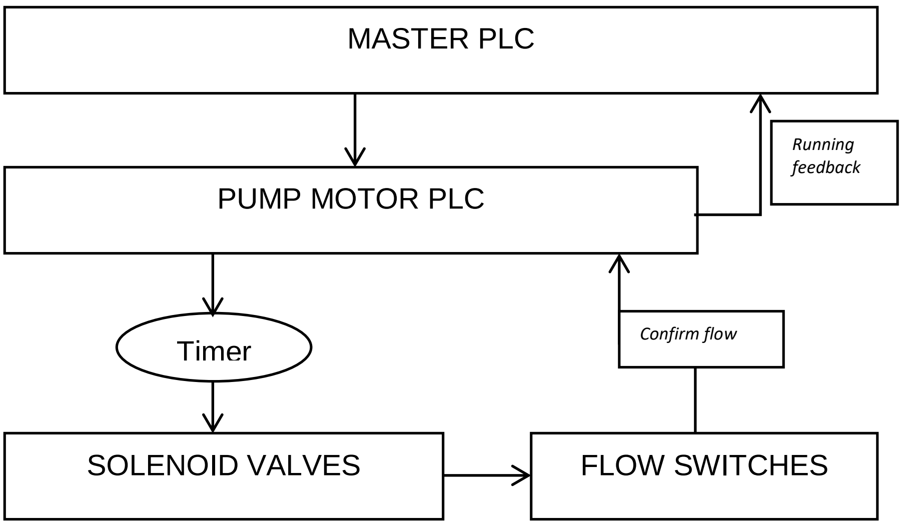

Figure 50 – Context diagram of the proposed automated solenoid valve control

Master PLC

The main function of the Master PLC is to send and receive information from the pump motor PLC's. The Master PLC also receives information from other field instruments, for example, dam levels etc. The Master PLC is an integral part of the Supervisory Control and Data Acquisition (SCADA) system which monitors the mine's operations closely. The SCADA provides a graphic user interface where mine employees can monitor their sections from the surface and have easy access and data of the actual performance of the equipment and systems.

Pump PLC

The pump PLC is a dedicated localised unit for a specific pump motor tasked with controlling and safely operating that motor. It is limited to only controlling the stop/start operations of the pump motor and to collect data from the instruments connected to the pump. The pump PLC controls all the internal pump motor operations, for example:

- Start-up sequence.
- Stop sequence.
- Ready to start signal.
- Alarm signal and trip signal.

All the tags must be readable by the SCADA, with all the non-critical warnings, alarms and trip signals reset remotely and all information to be displayed on the Human Machine Interface (HMI). Figure 50 shows the control loop required to incorporate the solenoid valves as part of the D5 level pump motor cooling system control. The pump PLC will control the functioning of the solenoid valves to supply the required motor cooling water flow, while the Master PLC will control the stop and start functions of the main clear water pumps.

6.3.3 Cooling water and washing water requirements on D5 level

On D5 level there are specific chilled water requirements that need to be analysed as part of the system design. The amount and types of pumps and their chilled water requirements and any extra chilled water requirements needs to be considered. Table 14 and Table 15 breaks down all the requirements of the chilled water requirements.

Table 14 – D# D5 level motor cooling specification

Motor type	Cooling water flow	Cooling water maximum inlet temperature	Cooling water inlet pressure
ALSTOM (1850 kW)	4.6 l/s	33.5°C	6.25 bar
ALSTOM (1110 kW)	2.6 l/s	33.5°C	6.25 bar

Table 15 – D# D5 level washing specifications

Description	Cooling water flow (per pump)	Cooling water inlet temperature	Cooling water inlet pressure
Washing	2 l/s (max)	Not applicable	5 bar

The maximum chilled water flow required on D5 level is 21.6 l/s and can be determined as follows:

- Two off 1850kW Alstom motor – 4.6 l/s each with a total of 9.2 l/s.

  and

- Four off 1110kW ABB motors - 2.6 l/s each with a total of 10.4l/s.

  and

- Washing - 2 l/s.

The layout of the system on D# D5 level as discussed from Chapter 6.1 can be seen in Figure 51:

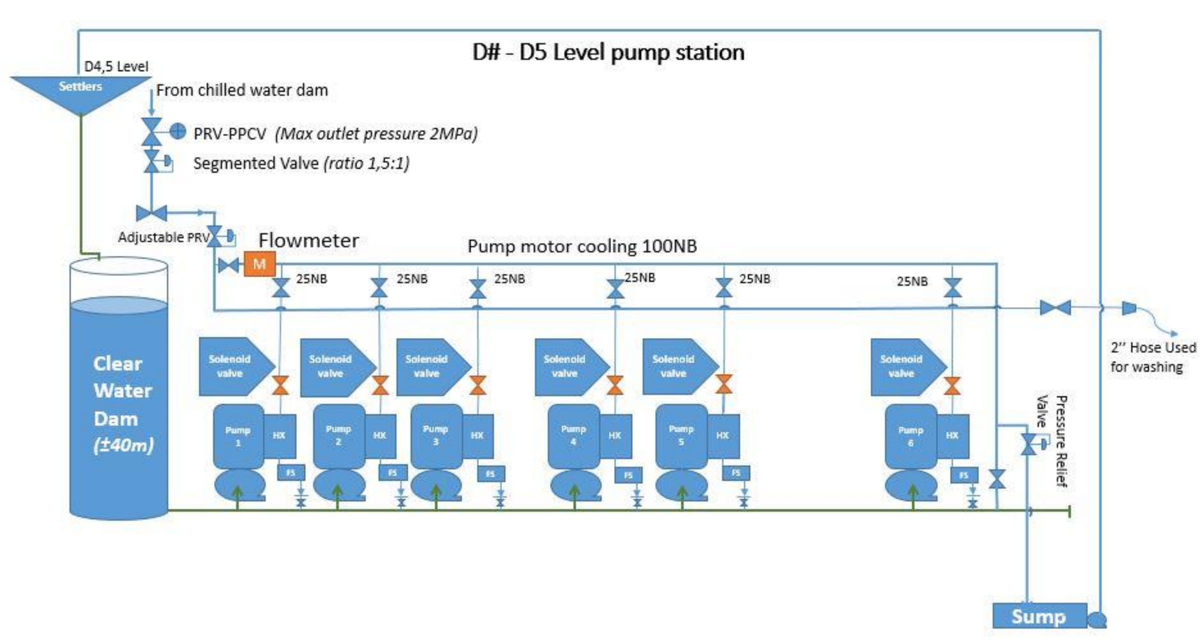

Figure 51 – D# D5 level pump station layout

The flowmeter in the system, marked M, only measures the water destined for motor cooling for accurate performance measuring. Figure 51 illustrates the complete system in detail that is fully discussed throughout the chapter thus far.

6.4 Calculations methodology

To accurately measure the chilled water flow baseline, a flowmeter was installed just before the first motor cooler. The baseline was recorded over a period of time to accurately represent an average value of the chilled water consumption on D5 level D#. The baseline period was approved by an independent Measurement and Verification (M&V) team which also measured and verified the results.

After the baseline was recorded and the required calculations were done by the M&V team, the baseline was plotted. The baseline will be used to measure performance and the reduction of chilled water flow due to the automated solenoid valve initiative. The installation of the proposed technology took place after the baseline was completed.

After installation of the mechanical, electrical and control components the commissioning of the project was done.

To calculate the amount of power saved by the initiative based on a flow value, the following equation was developed from Table 3:

$$Power\ saved\ \left(\frac{kW}{l/s}\right) = D5 + D4\ level + D3\ level + D0\ level + Fridge\ plant \qquad [9]$$

$$Power\ saved\ \left(\frac{kW}{l/s}\right) = 6.74 + 13.35 + 14.01 + 13.12 + 16.81$$

$$Power\ saved\ \left(\frac{kW}{l/s}\right) = 64.03$$

To calculate the amount of power saved by the initiative, an average chilled water flow saving needs to be calculated from actual data and be subtracted from the baseline to obtain a daily chilled water flow reduction. The average chilled water flow reduction can then be multiplied by the power saved figure as calculated by Equation 9. In the following figure, the baseline for D# D5 level is illustrated.

Figure 52 shows the impact of the chilled water reduction against the baseline.

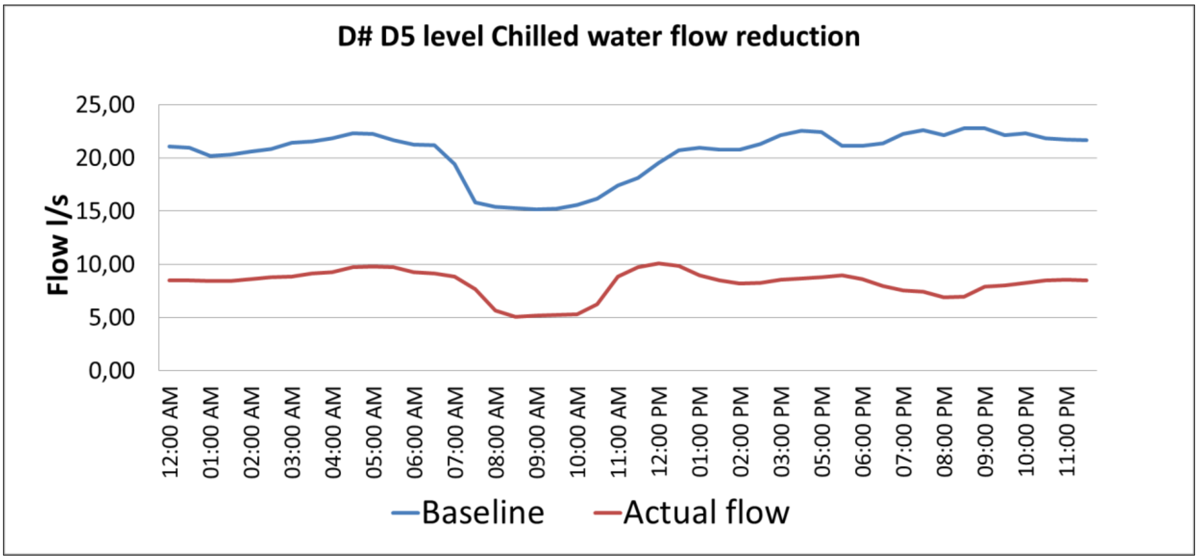

Figure 52 – D# D5 level Chilled water flow reduction

As can be seen, a significant amount of chilled water reduction has occurred on a daily basis. After the chilled water reduction intervention, the average chilled water flow reduction is 12.1 l/s which is 58% reduction in flow. Using Equation 9 this relates to a power saving of:

$$Power\ saved = 12.1\frac{l}{s} \times 64.03\frac{kW}{l/s}$$

$$Power\ saved = 774.76\ kW$$

The power saving can now be used to calculate the cost savings based on the same Megaflex tariffs as stipulated in Table 7 and Table 8. Table 16 and Table 17 contains the calculations for the daily cost savings.

Table 16 – D# D5 level daily cost saving calculation

DAILY SAVINGS = 775 kW			
WINTER	**Calculation**	**SUMMER**	**Calculation**
Weekday	775 kW x 24h x (107.6/100)	**Weekday**	775 kW x 24h x (62.59/100)
Saturday	775 kW x 24h x (56.47/100)	**Saturday**	775 kW x 24h x (48.18/100)
Sunday	775 kW x 24h x (49.4/100)	**Sunday**	775 kW x 24h x (43.99/100)

Table 17 – D# D5 level daily cost savings results

DAILY SAVINGS = 775 kW			
WINTER	**Calculation**	**SUMMER**	**Calculation**
Weekday	R 20 000	**Weekday**	R 11 600
Saturday	R 10 500	**Saturday**	R 9000
Sunday	R 9 200	**Sunday**	R 8 200

Taking these cost savings into account and calculating the annual cost savings, a significant amount in the region of R 4 million can be saved.

To verify whether the motors are operating within specification the motor winding and bearing temperatures were plotted against the baseline for the temperatures. Pump 8 with its allocated motor was the only motor that had operational temperature sensors. Figure 53 and Figure 54 shows the post-implementation motor winding and bearing temperatures compared to the baseline and how the performance temperatures are within the acceptable range. The winding temperature performed within 5% of the baseline, which is acceptable.

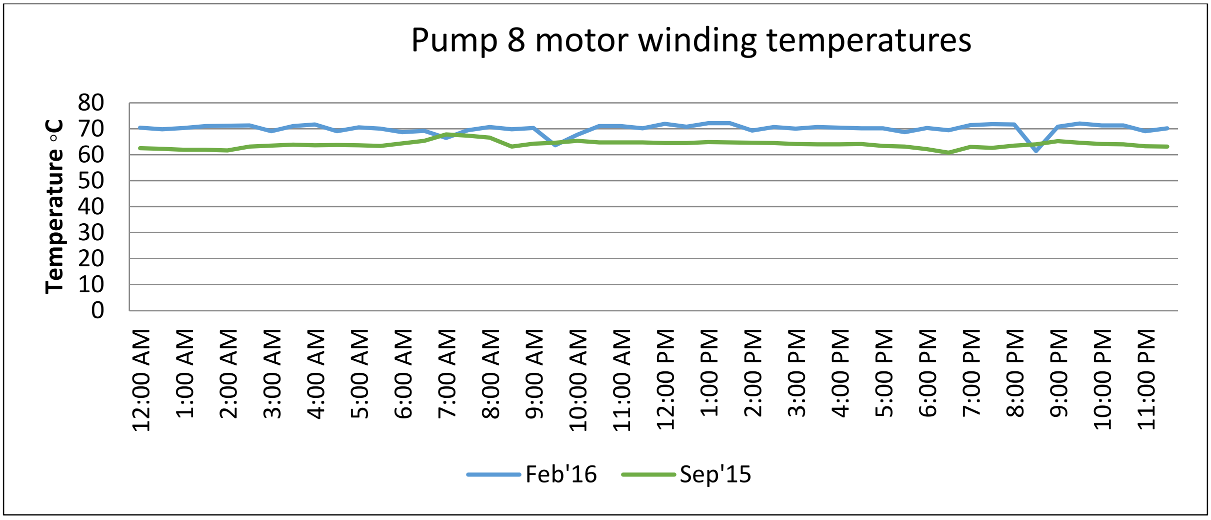

Figure 53 – Pump motor winding temperatures

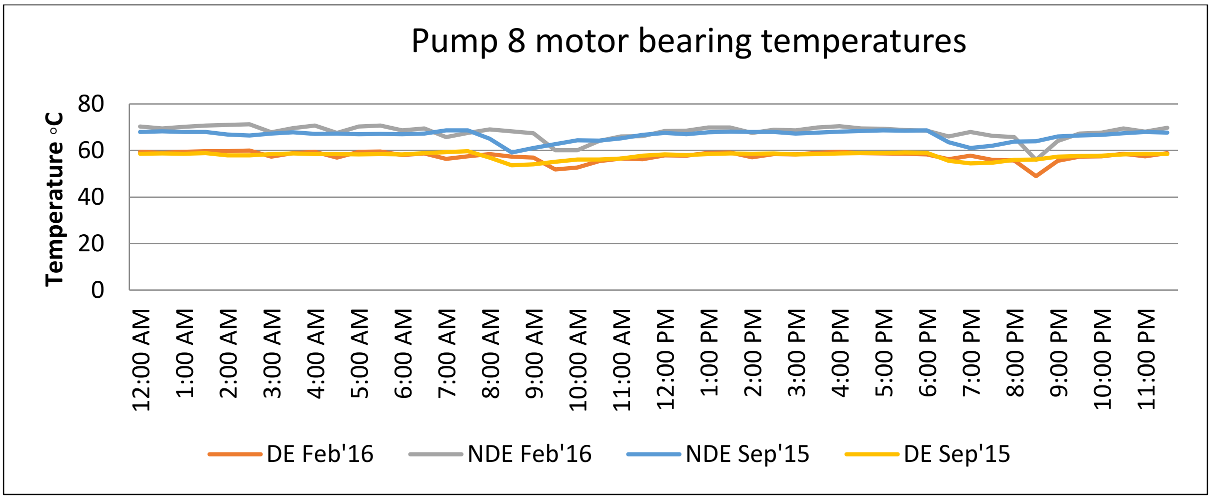

Figure 54 – Pump motor bearing temperatures

For further temperature and initiative performance graphs refer to Appendix – C. The bearing temperatures performed within specification and was not monitored as long as the winding temperatures due to the winding temperatures being the critical parameter.

This intervention proved to be a simple yet efficient way to realize cost savings and to eliminate the human factors which caused chilled water wastage. The significant financial cost savings realised proves to be a worthwhile endeavour and can easily be implemented at other sites.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

Electricity costs are rising and will keep rising as the global demand for energy is also projected to increase significantly over the span of a few years to come. Deep level gold mines consume a large portion of the electricity that Eskom generates and the mining sector is infamous for not consuming electricity responsibly and sparingly.

Previous studies conducted to reduce the electricity costs by means of engineering projects or solutions indicated that there are various areas and strategies that could bring about financial savings at a deep level gold mine. Peak clipping, load shifting and energy efficiency are the most common categories that any initiative can be categorised under.

As shown in this study the chilled water consumption plays a huge role in the mine's electricity expenses. Dewatering the mine by means of large pumps and to refrigerate the water again on the surface have serious cost implications. The aim of this study was to reduce the amount of chilled water that is consumed on a deep level gold mine and thereby reduce the electricity cost. The refrigeration plant will also benefit from a reduction in chilled water consumed underground as it will reduce the load on the refrigeration plant.

The large dewatering pump motors requires cooling to ensure safe and efficient operation of the motors. Underground pump motor cooling, which is known for consuming a significant amount of chilled water was investigated and it was found that there are multiple opportunities to reduce the chilled water consumption. Three initiatives were investigated as discussed in the previous chapters and implemented at a case study mine with the following savings realised as shown in Table 18.

Table 18 – Savings summary

Initiatives	Energy demand savings	Annual Financial savings
Air coolers	1134 kW	R 5 700 000
BPS	700kW	R 3 600 000
Auto Solenoids	775kW	R 4 000 000
TOTAL	**2609 kW**	**R 13 300 000**

It is recommended that the three proven technologies can be implemented and rolled out to various sites and mines to save significant amounts of chilled water which will have an enormous effect on the electricity cost to the mines as proven by this study. By reducing the chilled water consumption, the pumping and refrigeration load will also benefit in terms of lifetime extension and financial benefits.

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APPENDIX A – CONVERSION TO AIR COOLING

The performance of the conversion to air cooling initiative is constant as the chilled water feed has been blanked off. It is therefore not necessary to include every month's performance graphs as each month will be identical to the previous one. All that differs is the financial saving due to the Eskom Megaflex tariff structure. Underneath is a graph to illustrate the constant chilled water flow savings performance.

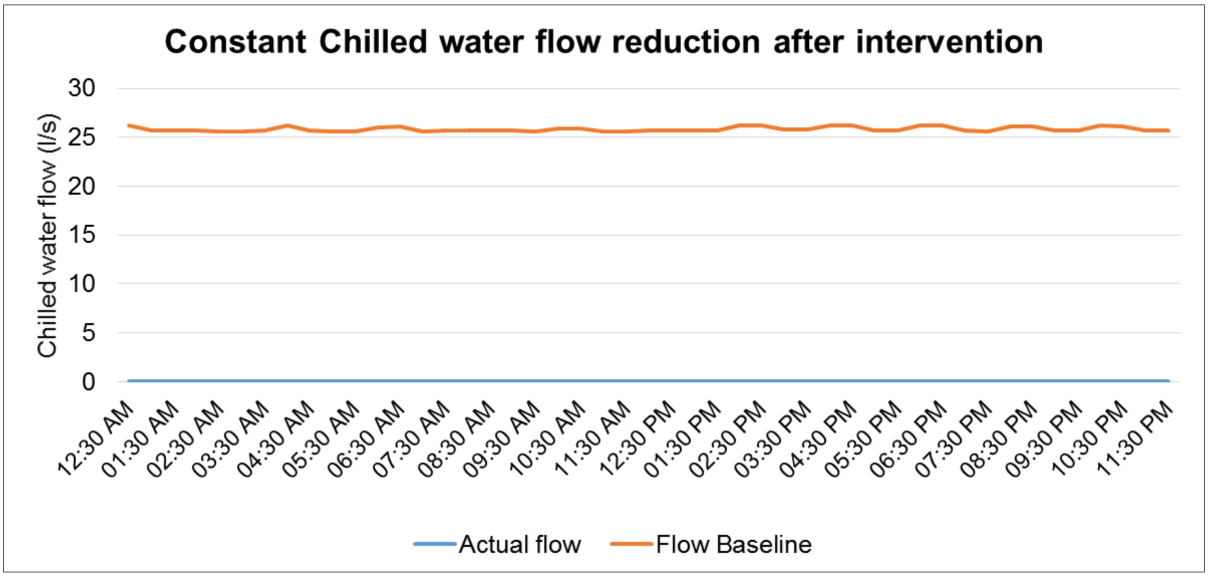


Figure 55 – Constant chilled water reduction of Energy savings initiative 1

The temperature data of the air cooler initiative has been evaluated for a one year period to analyse the sustainability and technical performance of the initiative. The graphs for the period August 2015 up and till July 2016 can be seen underneath:

August 2015:

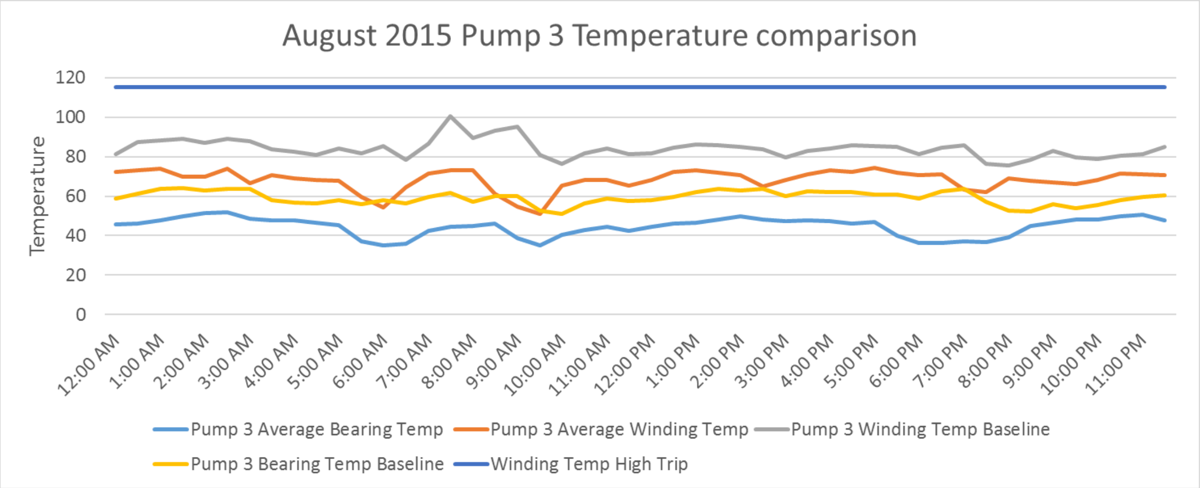


Figure 56 – A/C Aug 2015 Pump 3 Temperatures

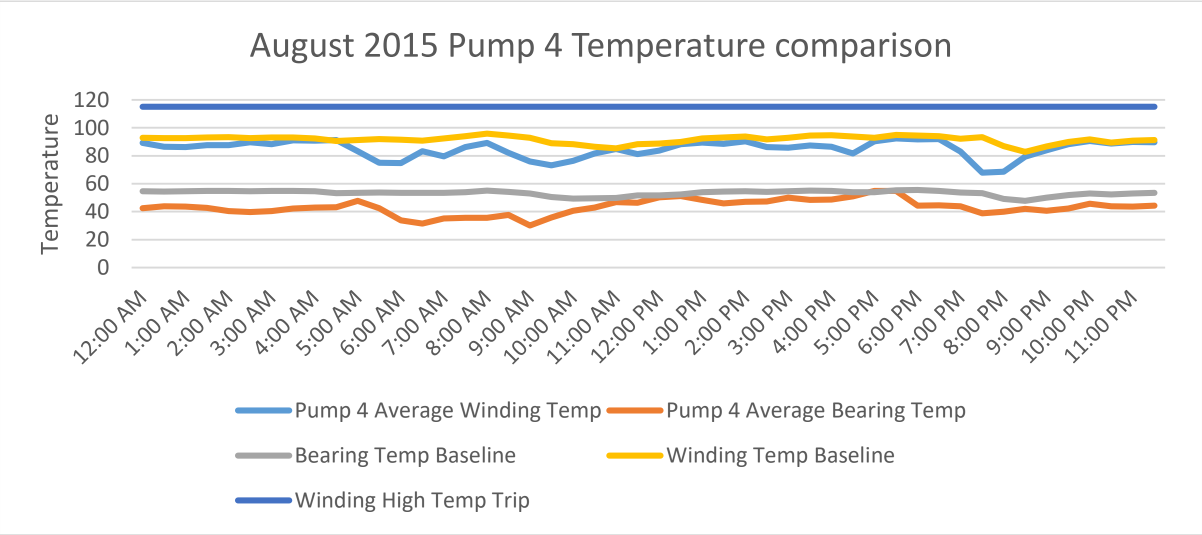


Figure 57 – A/C Aug 2015 Pump 4 Temperatures

September 2015:

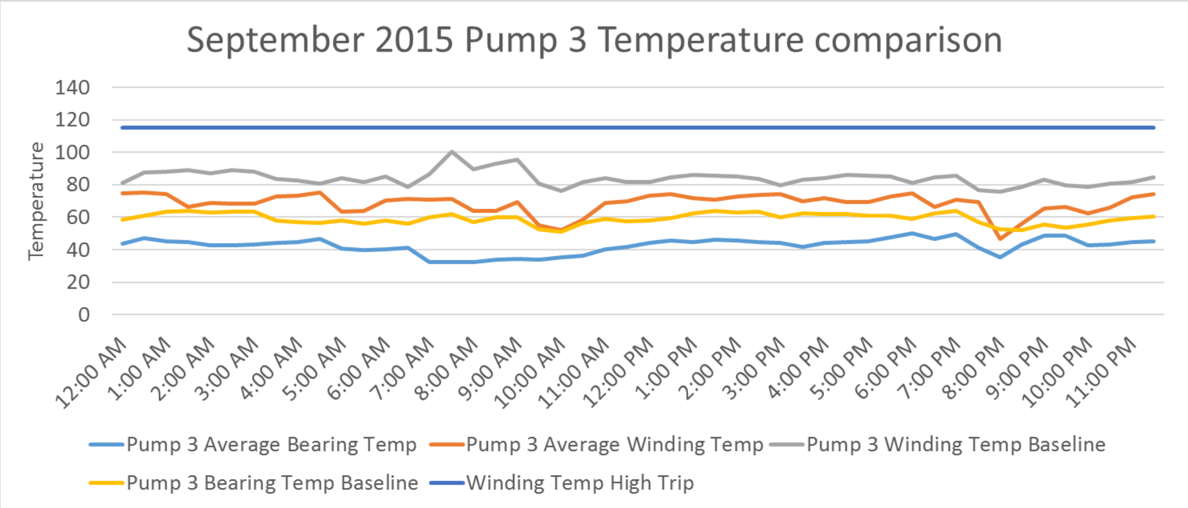


Figure 58 – A/C Sept 2015 Pump 3 Temperatures

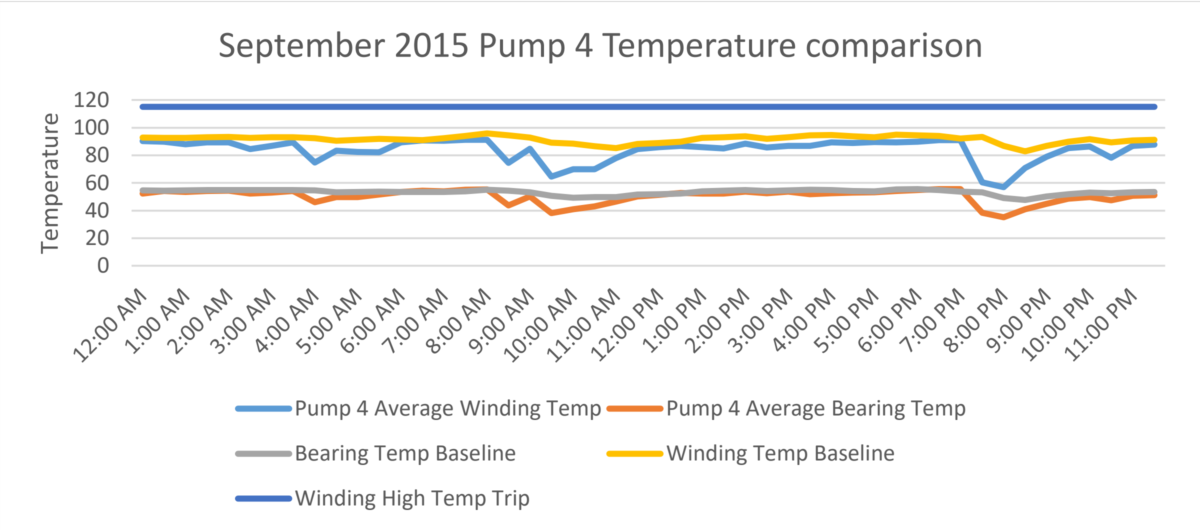


Figure 59 – A/C Sept 2015 Pump 4 Temperatures

October 2015:

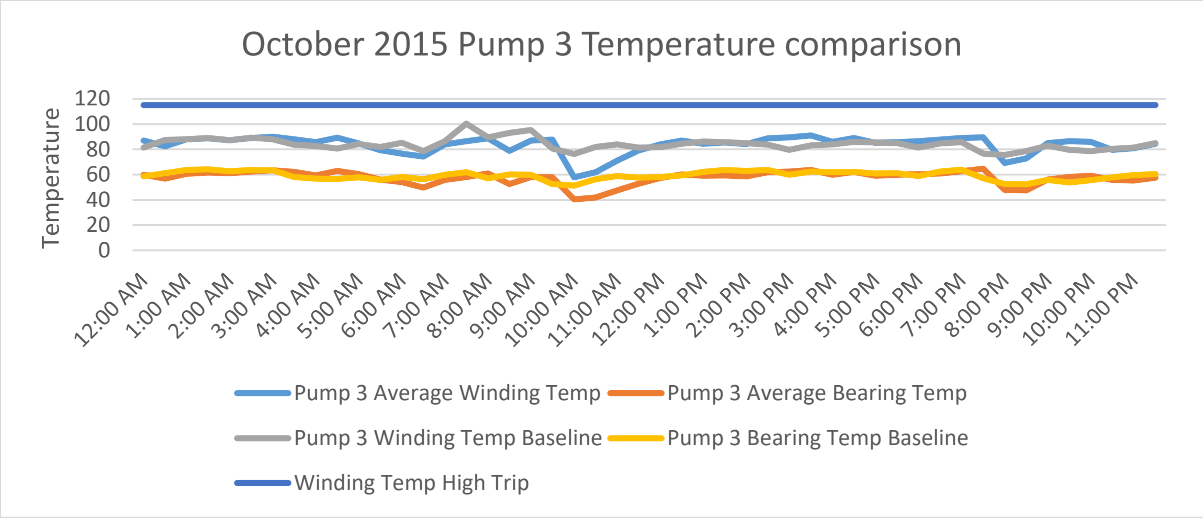


Figure 60 – A/C Oct 2015 Pump 3 Temperatures

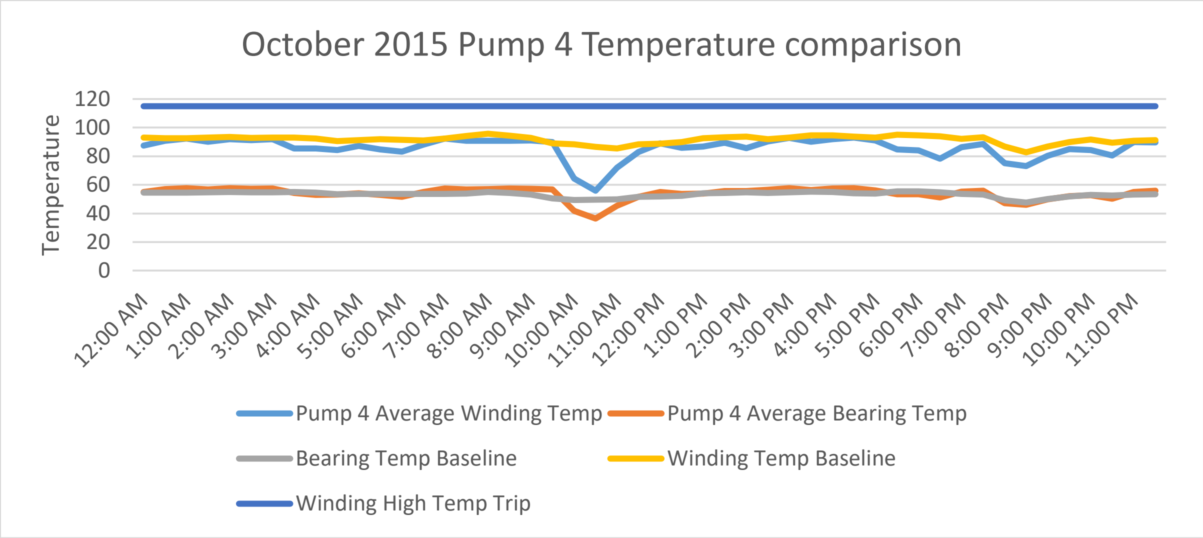


Figure 61 – A/C Oct 2015 Pump 4 Temperatures

November 2015:

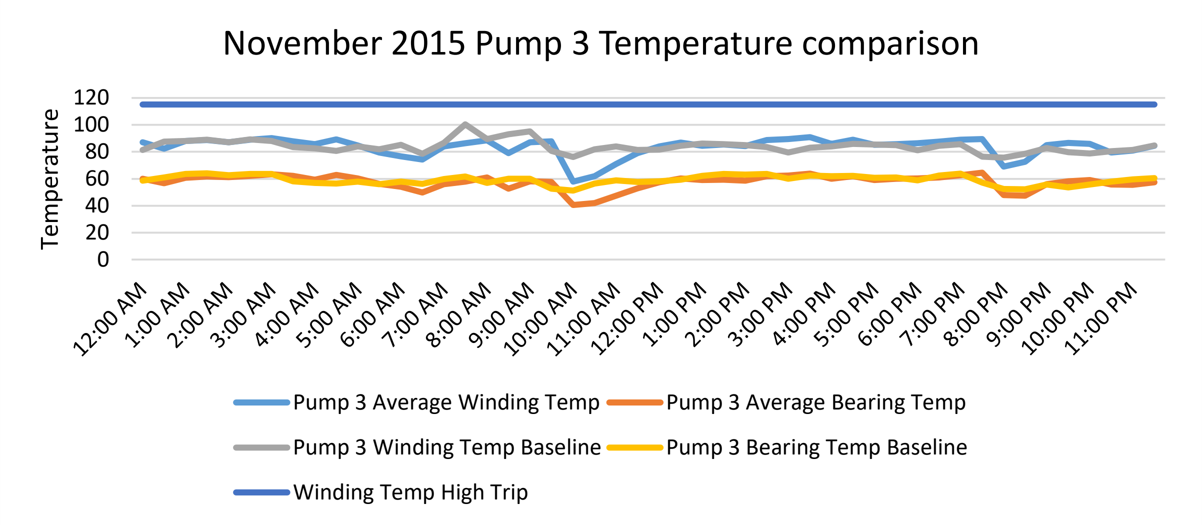


Figure 62 – A/C Nov 2015 Pump 3 Temperatures

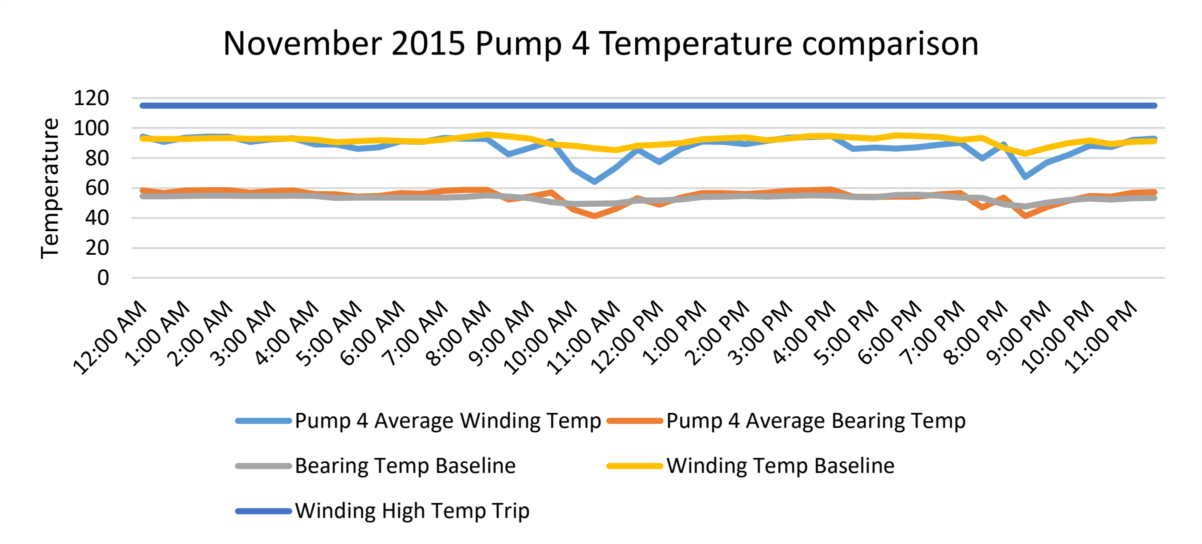


Figure 63 – A/C Nov 2015 Pump 4 Temperatures

December 2015:

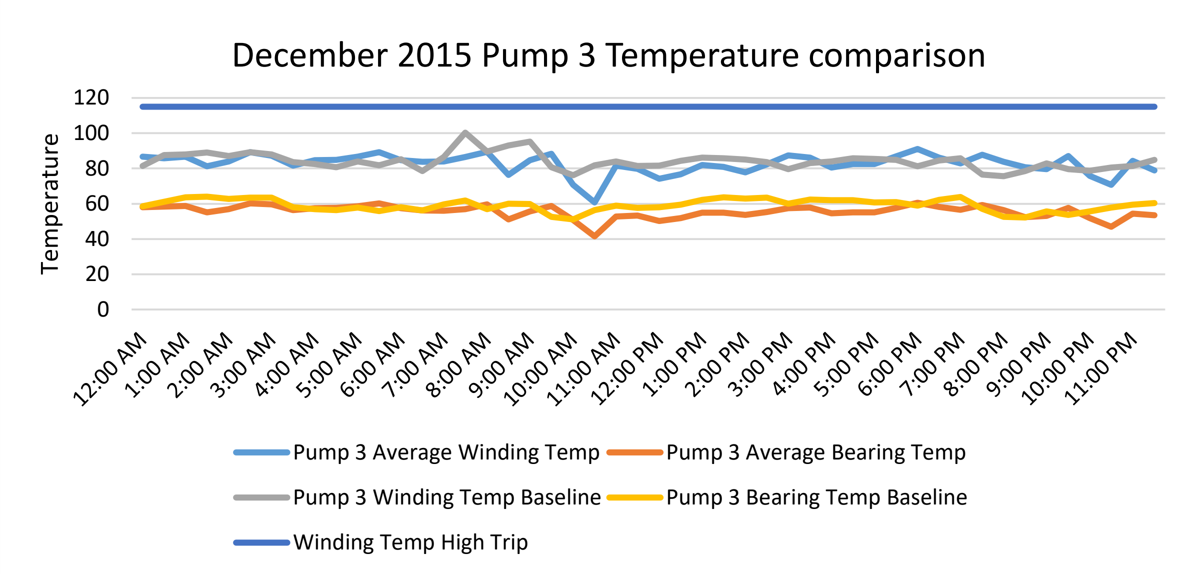


Figure 64 – A/C Dec 2015 Pump 3 Temperatures

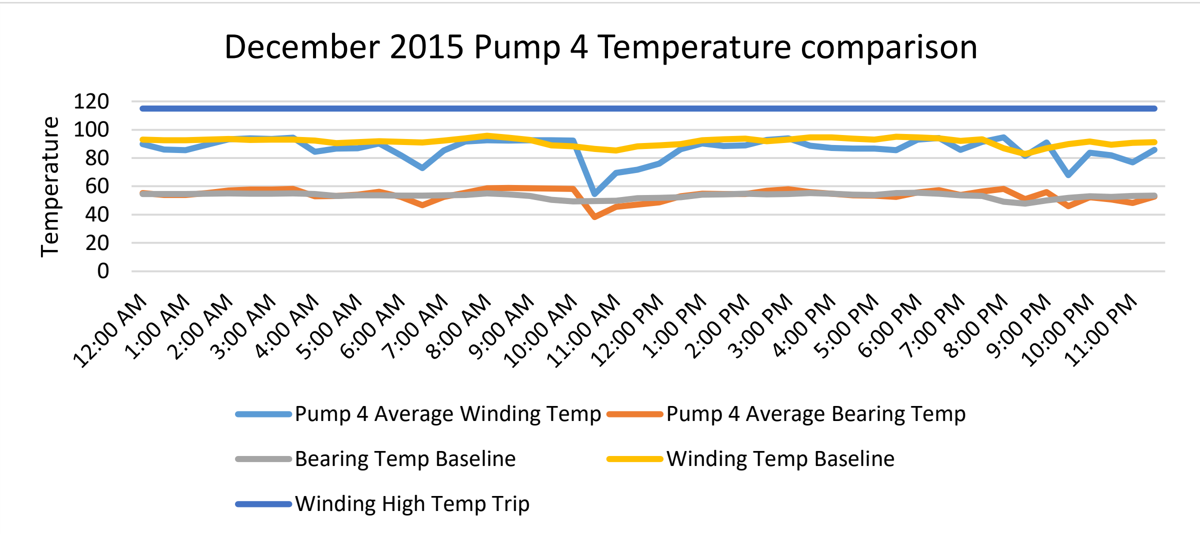


Figure 65 – A/C Dec 2015 Pump 4 Temperatures

January 2016:

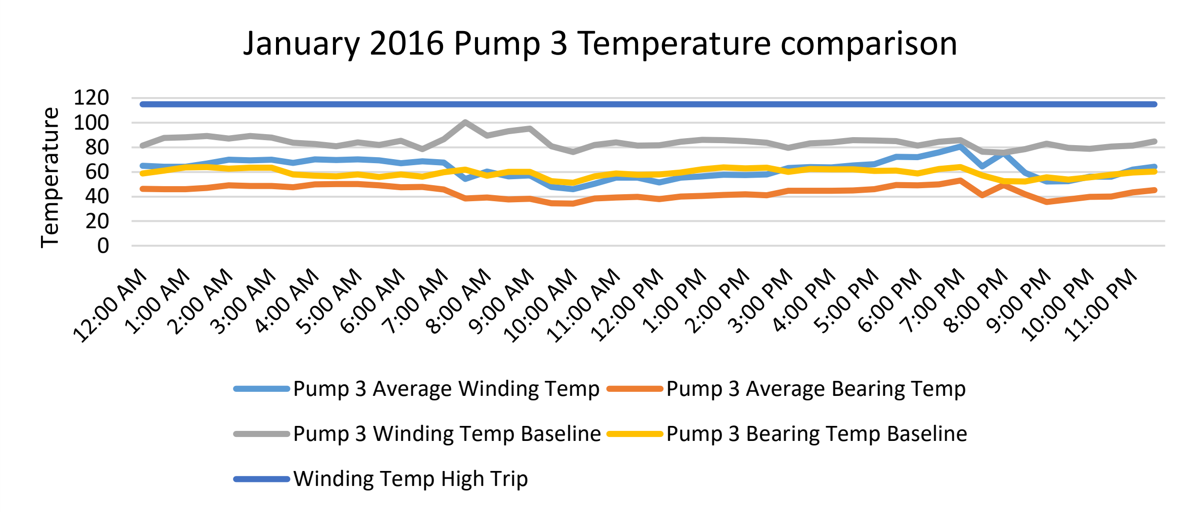


Figure 66 – A/C Jan 2016 Pump 3 Temperatures

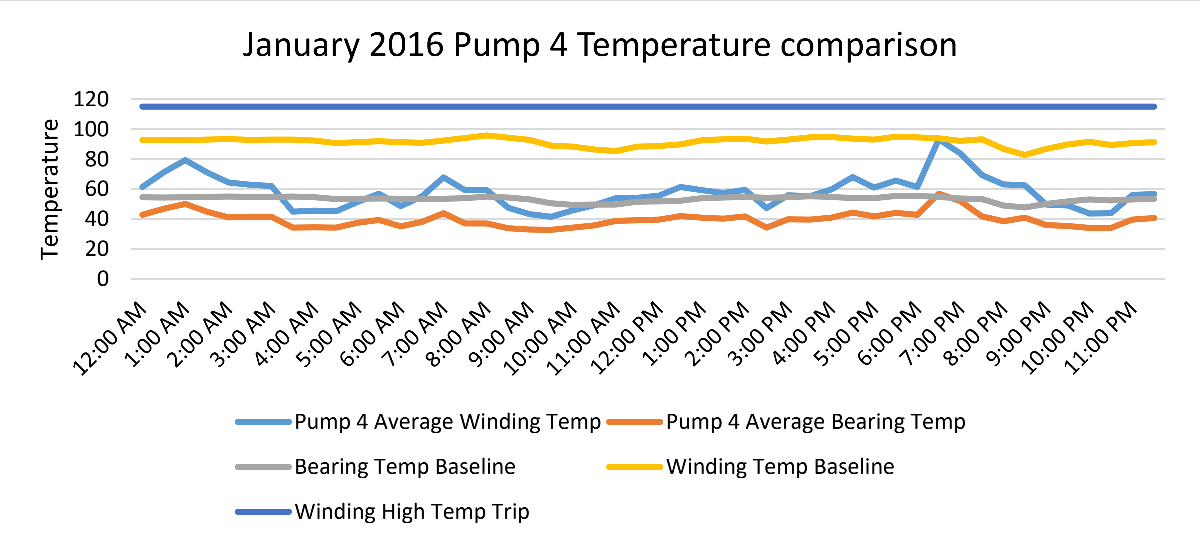


Figure 67 – A/C Jan 2016 Pump 4 Temperatures

February 2016:

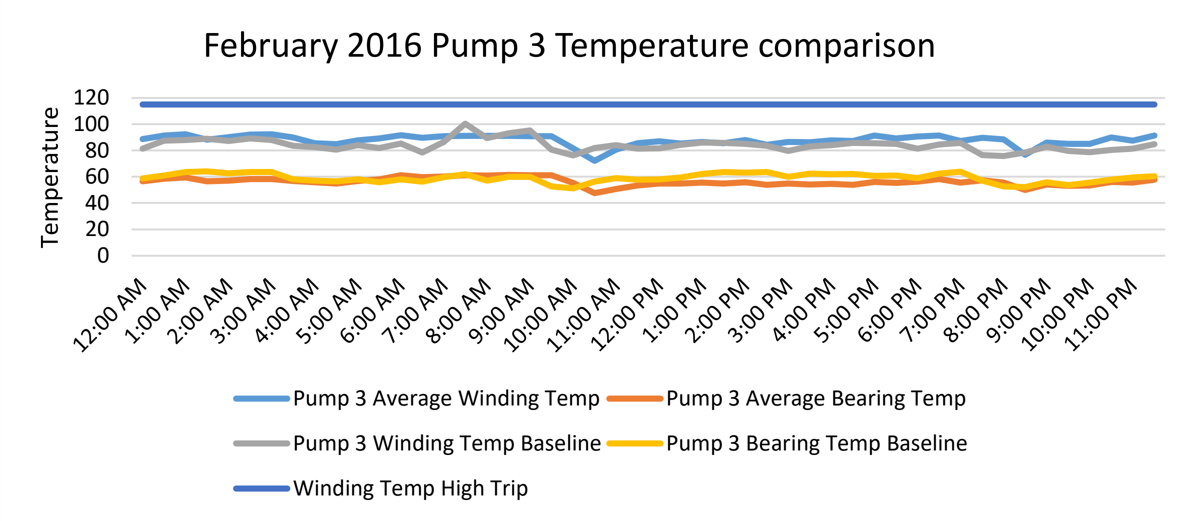


Figure 68 – A/C Feb 2016 Pump 3 Temperatures

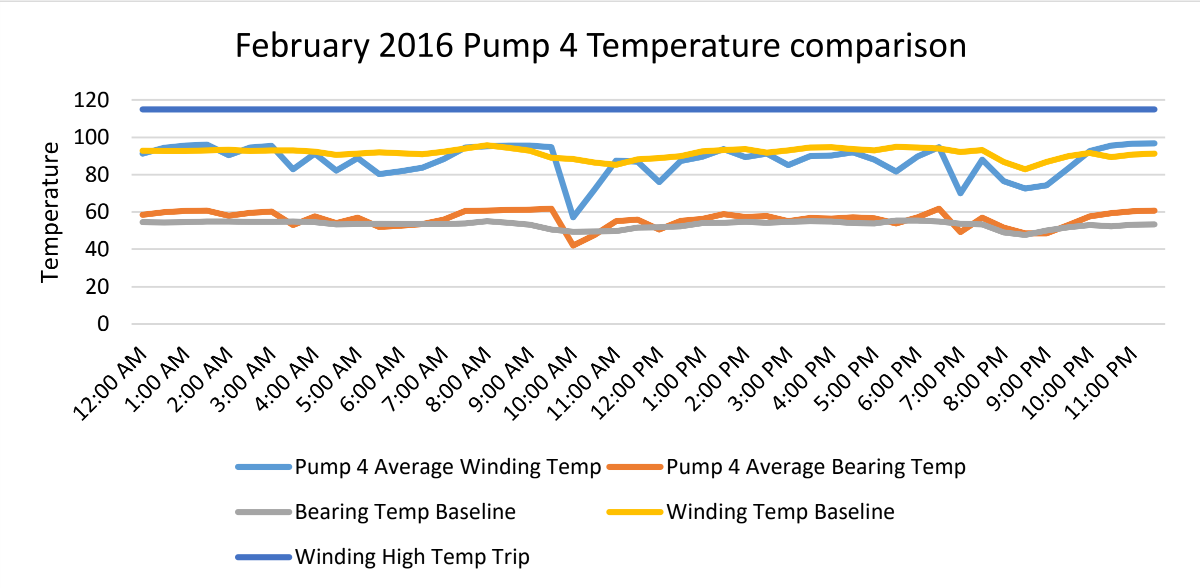


Figure 69 – A/C Feb 2016 Pump 4 Temperatures

March 2016:

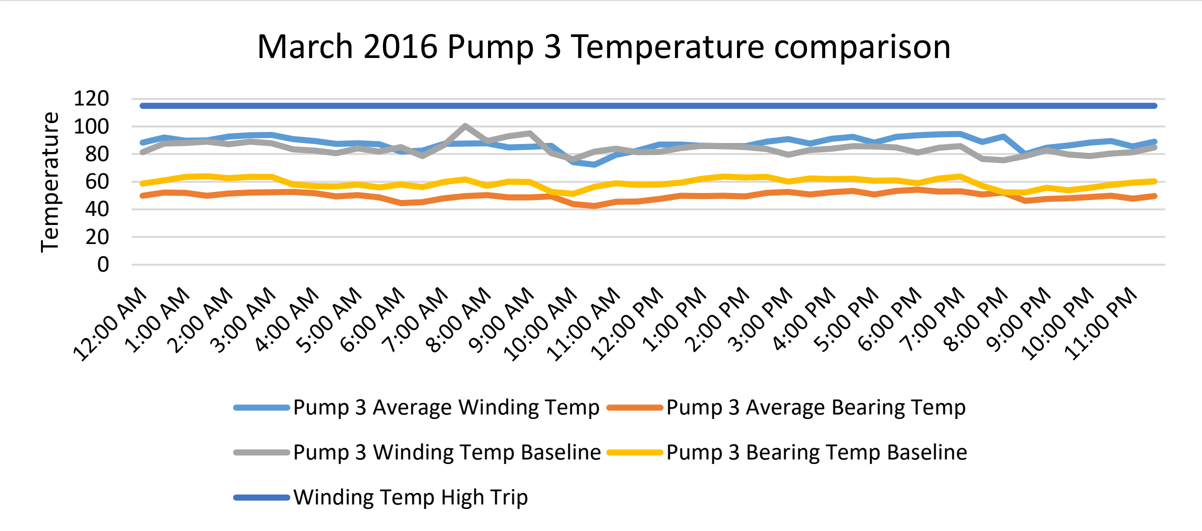


Figure 70 – A/C Mar 2016 Pump 3 Temperatures

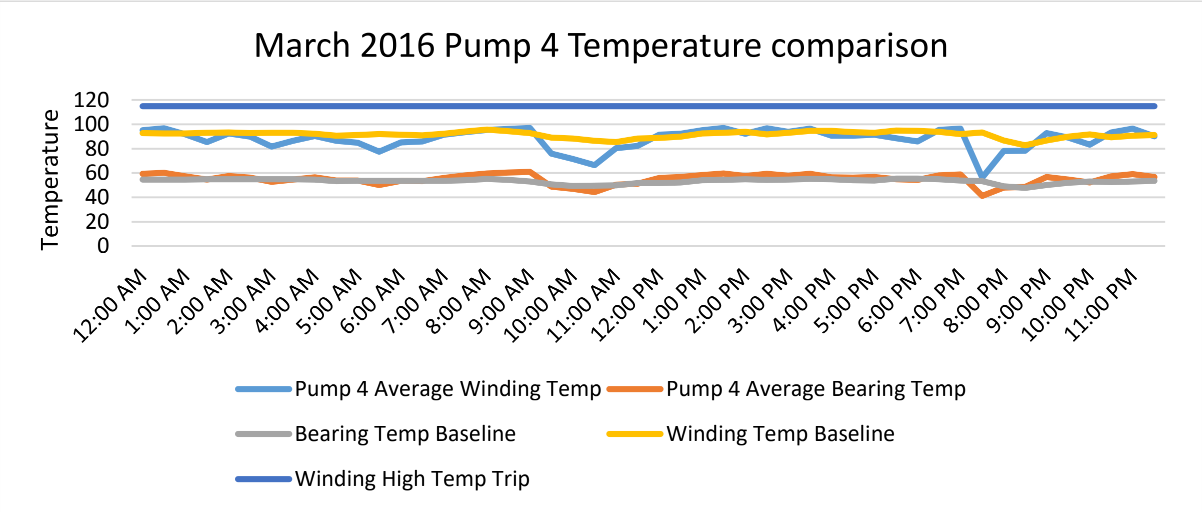


Figure 71 – A/C Mar 2016 Pump 4 Temperatures

April 2016:

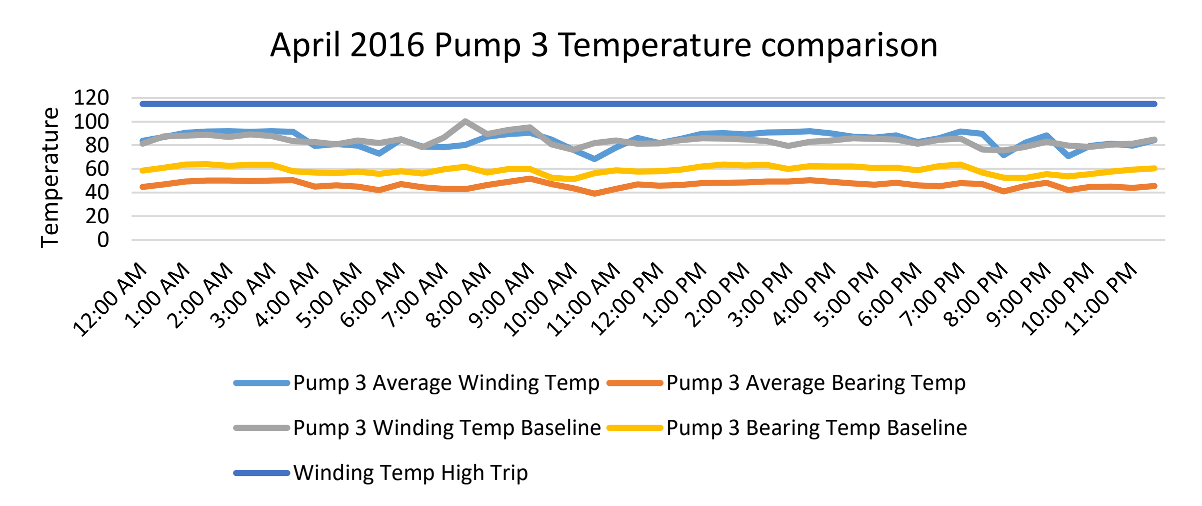


Figure 72 – A/C Apr 2016 Pump 3 Temperatures

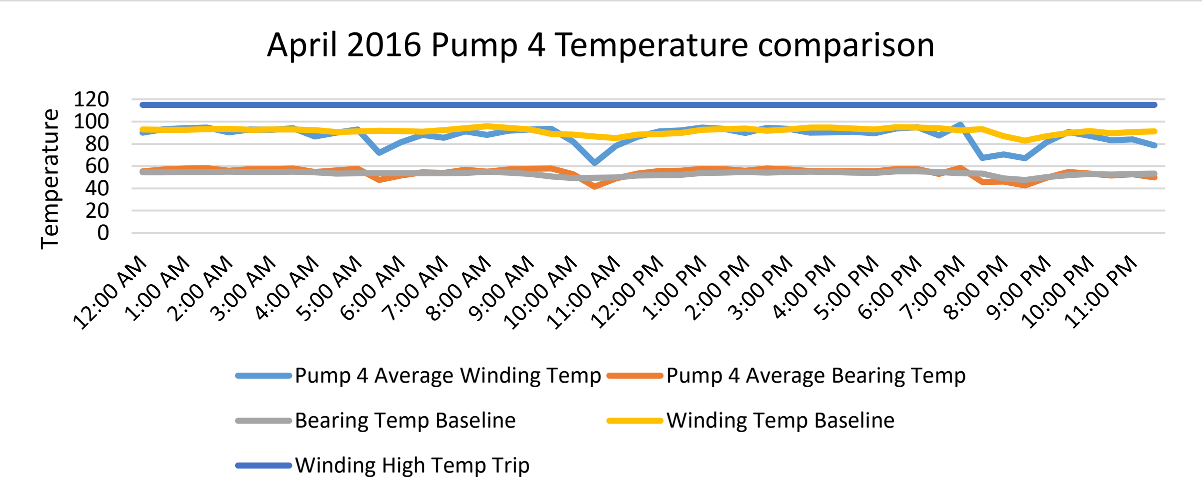


Figure 73 – A/C Apr 2016 Pump 4 Temperatures

May 2016:

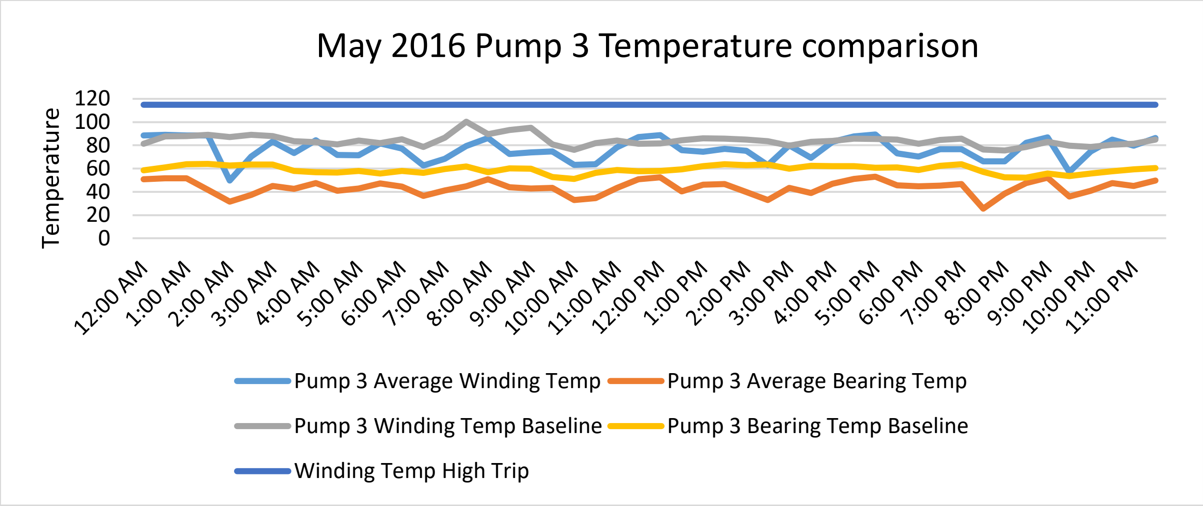


Figure 74 – A/C May 2016 Pump 3 Temperatures

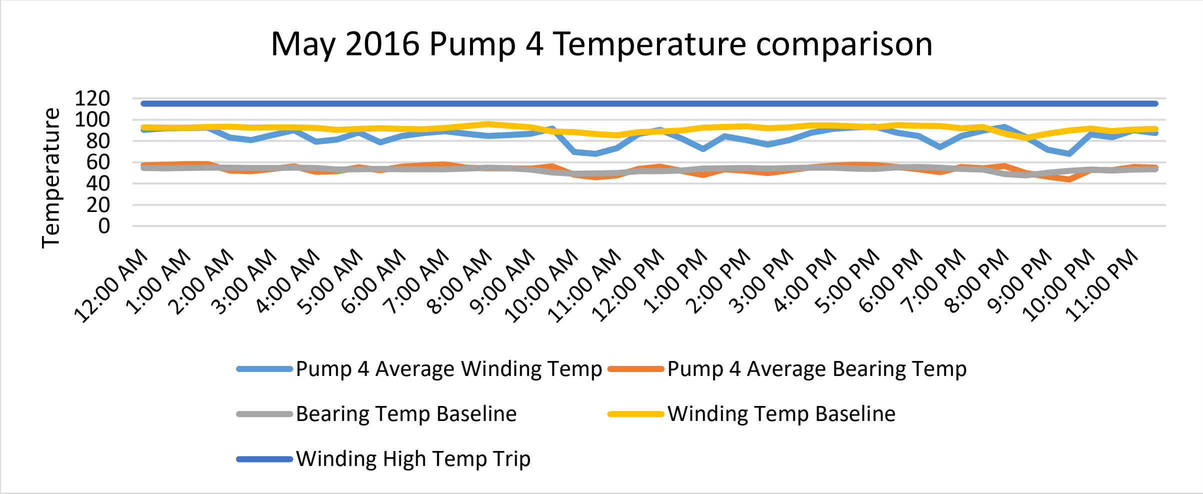


Figure 75 – A/C May 2016 Pump 4 Temperatures

June 2016:

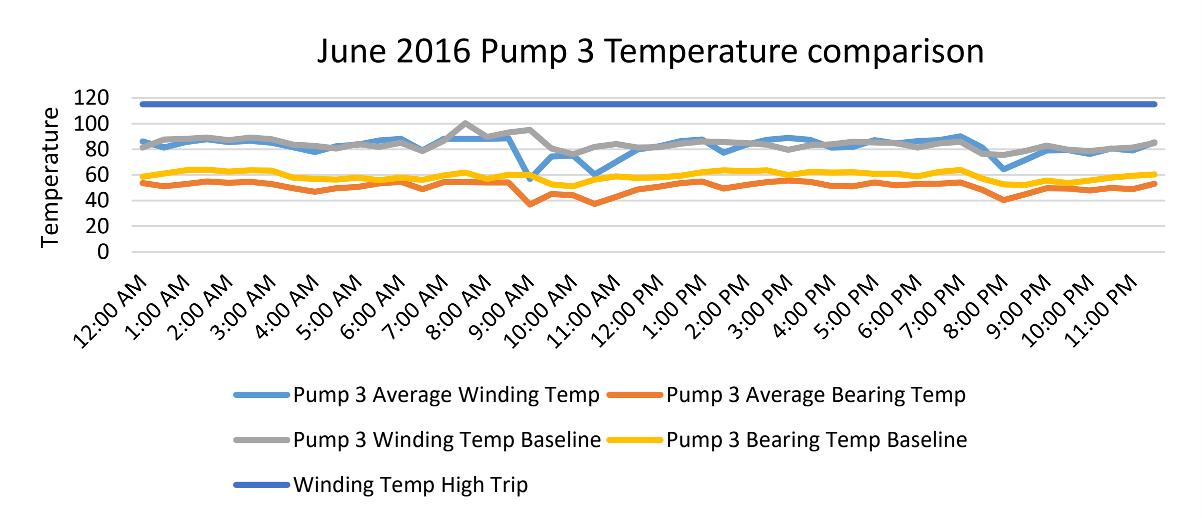


Figure 76 – A/C June 2016 Pump 3 Temperatures

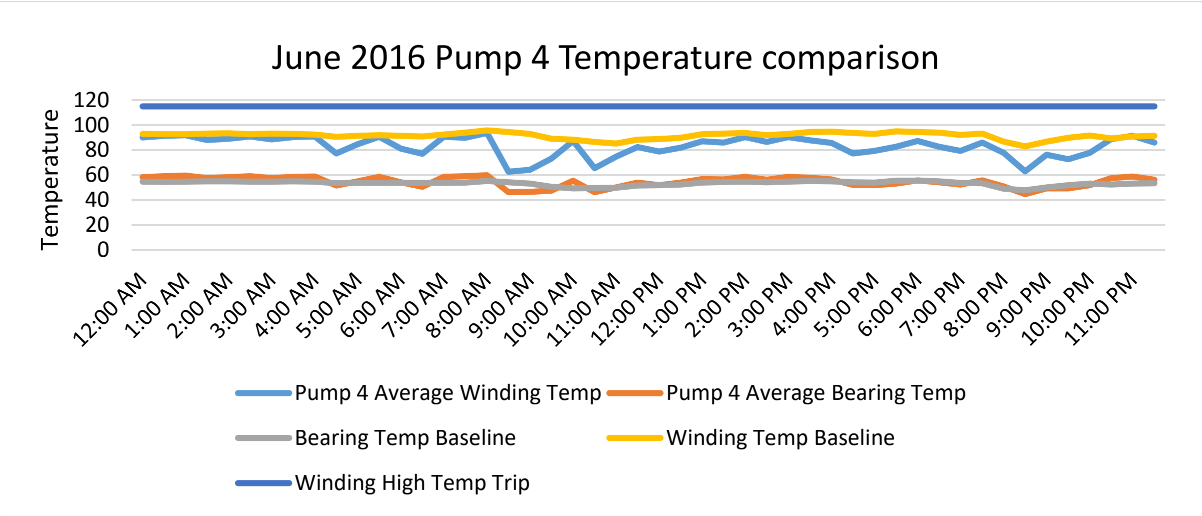


Figure 77 – A/C June 2016 Pump 4 Temperatures

July 2016:

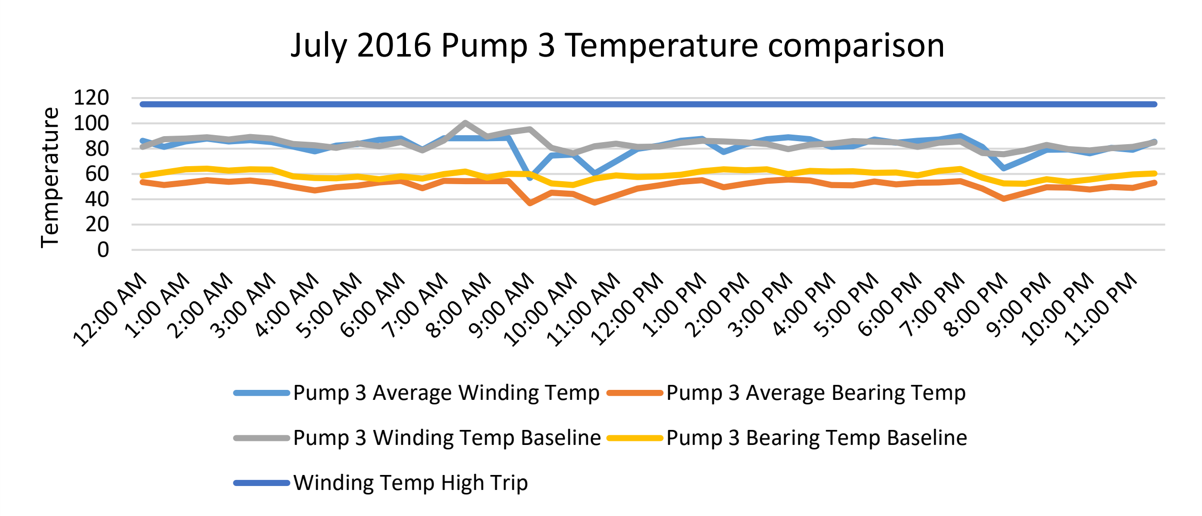


Figure 78 – A/C Jul 2016 Pump 3 Temperatures

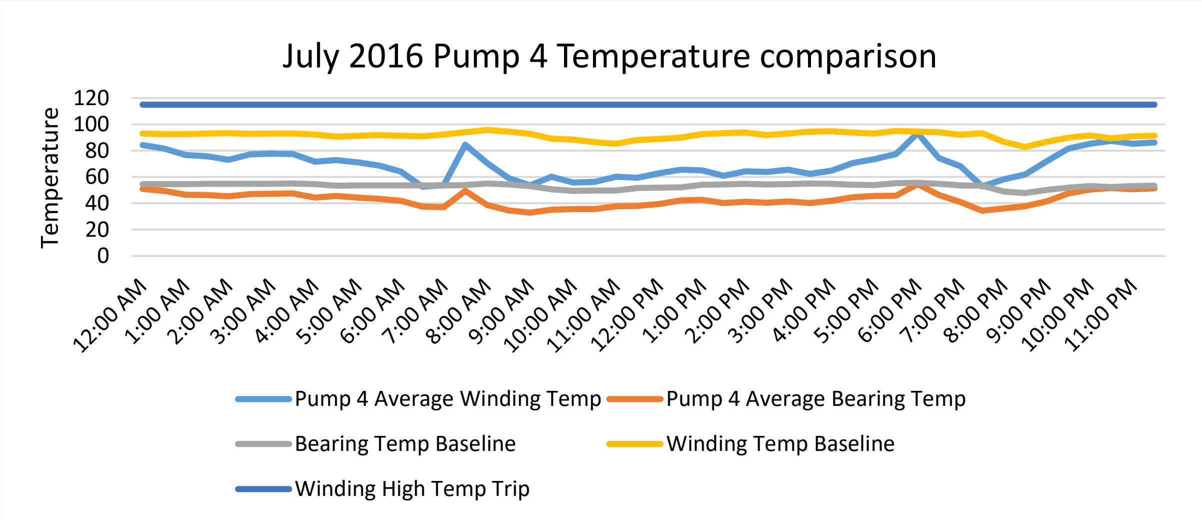


Figure 79 – A/C Jul 2016 Pump 4 Temperatures

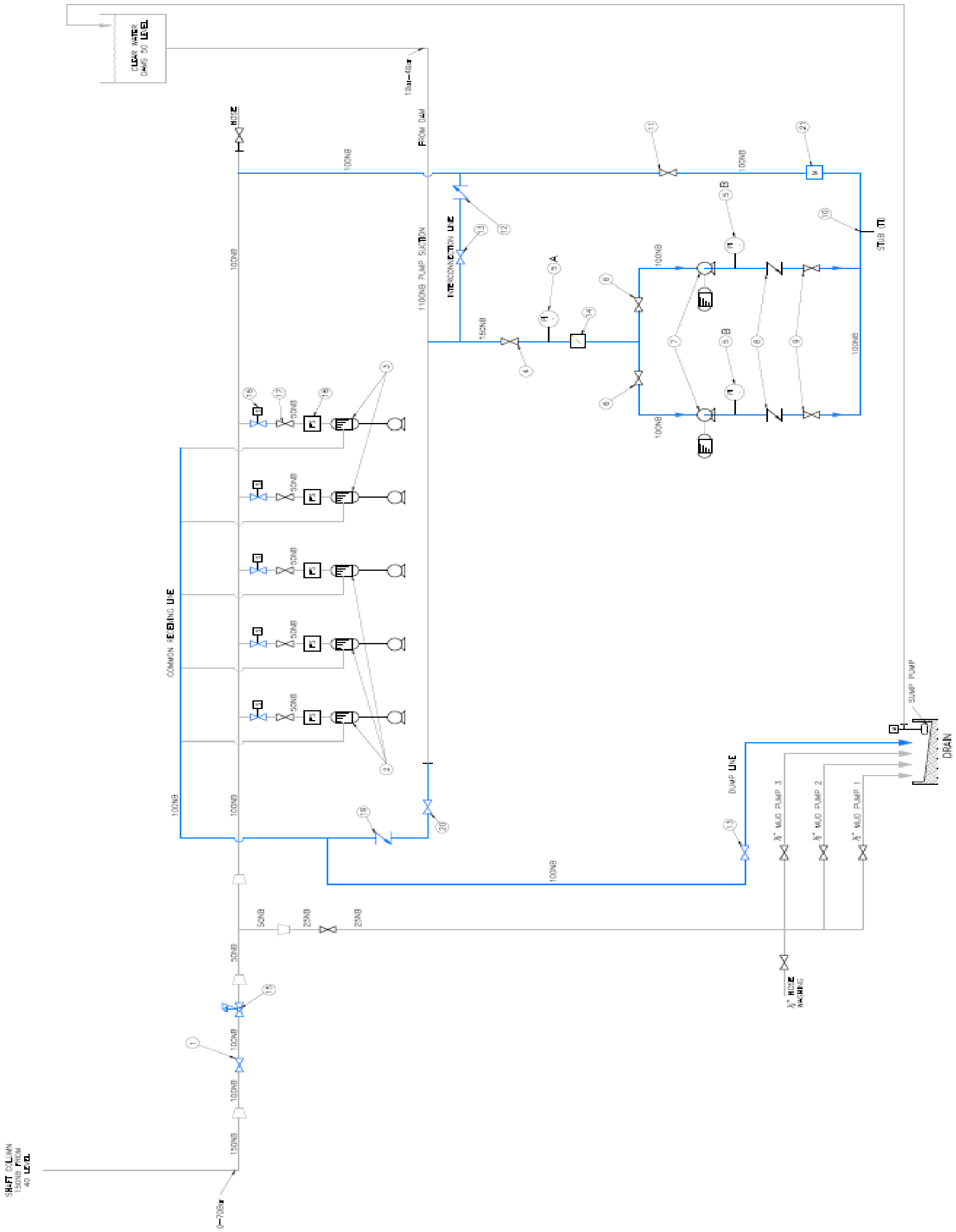
APPENDIX B1 – FLOW SIMULATION

A detailed flow simulation has been done to calculate the required flow for each and every situation that might present itself and can be found.

Table 19 – Detailed flow simulation

Water Flow rate (l/s)							Water pressure at intake (bar)						VSD P = 5 Bar (gauge)	
Clear water dam %	1x Large Pump	1x Small Pump	1x Small Pump	1x Mud pump	Hose 1	Hose 2	1x Large Pump	1x Small Pump	1x Small Pump	1x Mud pump	Hose 1	Hose 2	Booster pump rpm	System Flow
(1.8 bar) 20%	11.73						4.28						2400	11.7
(3 bar) 50%	10.10						4.58						2068	10.1
(4.2 bar) 80%	7.80						4.75						1600	7.8
Water Flow rate (l/s)							Water pressure at intake (bar)							
Clear water dam %	1x Large Pump	1x Small Pump	1x Small Pump	1x Mud pump	Hose 1	Hose 2	1x Large Pump	1x Small Pump	1x Small Pump	1x Mud pump	Hose 1	Hose 2	Booster pump rpm	System Flow
(1.8 bar) 20%	11.66			0.74			4.23			4.95			2450	12.4
(3 bar) 50%	9.93			0.74			4.50			4.99			2100	10.7
(4.2 bar) 80%	7.95			0.75			4.82			5.08			1700	8.7
Water Flow rate (l/s)							Water pressure at intake (bar)							
Clear water dam %	1x Large Pump	1x Small Pump	1x Small Pump	1x Mud pump	Hose 1	Hose 2	1x Large Pump	1x Small Pump	1x Small Pump	1x Mud pump	Hose 1	Hose 2	Booster pump rpm	System Flow
(1.8 bar) 20%	11.78			0.73	2.93		4.30			4.79	4.59		2750	15.4
(3 bar) 50%	10.02			0.73	2.94		4.55			4.80	4.60		2400	13.7
(4.2 bar) 80%	7.76			0.72	2.92		4.74			4.75	4.55		1950	11.4
Water Flow rate (l/s)							Water pressure at intake (bar)							
Clear water dam %	1x Large Pump	1x Small Pump	1x Small Pump	1x Mud pump	Hose 1	Hose 2	1x Large Pump	1x Small Pump	1x Small Pump	1x Mud pump	Hose 1	Hose 2	Booster pump rpm	System Flow
(1.8 bar) 20%	11.55			0.68	2.71	2.71	4.17			4.19	3.74	3.74	2971	17.7
(3 bar) 50%	9.89			0.69	2.74	2.74	4.48			4.27	3.81	3.81	2650	16.1
(4.2 bar) 80%	7.82			0.69	2.75	2.75	4.76			4.32	3.85	3.85	2250	14.0
Water Flow rate (l/s)							Water pressure at intake (bar)							
Clear water dam %	1x Large Pump	1x Small Pump	1x Small Pump	1x Mud pump	Hose 1	Hose 2	1x Large Pump	1x Small Pump	1x Small Pump	1x Mud pump	Hose 1	Hose 2	Booster pump rpm	System Flow
(1.8 bar) 20%		10.69						4.27					2300	10.7
(3 bar) 50%		9.29						4.63					2000	9.3
(4.2 bar) 80%		7.41						4.89					1600	7.4
Water Flow rate (l/s)							Water pressure at intake (bar)							
Clear water dam %	1x Large Pump	1x Small Pump	1x Small Pump	1x Mud pump	Hose 1	Hose 2	1x Large Pump	1x Small Pump	1x Small Pump	1x Mud pump	Hose 1	Hose 2	Booster pump rpm	System Flow
(1.8 bar) 20%		10.86		0.75				4.38		5.03			2400	11.6
(3 bar) 50%		9.30		0.75				4.64		5.08			2068	10.1
(4.2 bar) 80%		7.11		0.75				4.76		4.97			1600	7.9
Water Flow rate (l/s)							Water pressure at intake (bar)							
Clear water dam %	1x Large Pump	1x Small Pump	1x Small Pump	1x Mud pump	Hose 1	Hose 2	1x Large Pump	1x Small Pump	1x Small Pump	1x Mud pump	Hose 1	Hose 2	Booster pump rpm	System Flow
(1.8 bar) 20%		10.78		0.72	2.92			4.33		4.73	4.53		2650	14.4
(3 bar) 50%		9.12		0.72	2.91			4.54		4.73	4.53		2300	12.8
(4.2 bar) 80%		7.45		0.72	2.91			4.71		4.71	4.51		1950	11.1
Water Flow rate (l/s)							Water pressure at intake (bar)							
Clear water dam %	1x Large Pump	1x Small Pump	1x Small Pump	1x Mud pump	Hose 1	Hose 2	1x Large Pump	1x Small Pump	1x Small Pump	1x Mud pump	Hose 1	Hose 2	Booster pump rpm	System Flow
(1.8 bar) 20%		10.72		0.69	2.73	2.73		4.29		4.25	3.79	3.79	2900	16.9
(3 bar) 50%		9.02		0.68	2.72	2.72		4.49		4.23	3.77	3.77	2550	15.2
(4.2 bar) 80%		7.05		0.69	2.73	2.73		4.73		4.26	3.80	3.80	2150	13.2
Water Flow rate (l/s)							Water pressure at intake (bar)							
Clear water dam %	1x Large Pump	1x Small Pump	1x Small Pump	1x Mud pump	Hose 1	Hose 2	1x Large Pump	1x Small Pump	1x Small Pump	1x Mud pump		Hose 2	Booster pump rpm	System Flow
(1.8 bar) 20%		9.26	9.30					3.51	3.52				2971	18.6
(3 bar) 50%		8.88	8.92					4.50	4.50				2850	17.8
(4.2 bar) 80%		7.00	7.03					4.76	4.77				2250	14.0
Water Flow rate (l/s)							Water pressure at intake (bar)							
Clear water dam %	1x Large Pump	1x Small Pump	1x Small Pump	1x Mud pump	Hose 1	Hose 2	1x Large Pump	1x Small Pump	1x Small Pump	1x Mud pump	Hose 1	Hose 2	Booster pump rpm	System Flow
(1.8 bar) 20%		9.02	9.06	0.65				3.37	3.38	3.79			2971	18.7
(3 bar) 50%		8.99	9.03	0.74				4.56	4.56	4.96			2971	18.8
(4.2 bar) 80%		7.04	7.08	0.74				4.78	4.79	4.99			2350	14.9
Water Flow rate (l/s)							Water pressure at intake (bar)							
Clear water dam %	1x Large Pump	1x Small Pump	1x Small Pump	1x Mud pump	Hose 1	Hose 2	1x Large Pump	1x Small Pump	1x Small Pump	1x Mud pump	Hose 1	Hose 2	Booster pump rpm	System Flow
(1.8 bar) 20%		8.16	8.21	0.58	2.34			2.92	2.93	3.09	2.96		2971	19.3
(3 bar) 50%		7.98	8.04	0.67	2.72			4.03	4.04	4.12	3.95		2971	19.4
(4.2 bar) 80%		7.03	7.08	0.72	2.92			4.78	4.79	4.74	4.54		2700	17.8
Water Flow rate (l/s)							Water pressure at intake (bar)							
Clear water dam %	1x Large Pump	1x Small Pump	1x Small Pump	1x Mud pump	Hose 1	Hose 2	1x Large Pump	1x Small Pump	1x Small Pump	1x Mud pump	Hose 1	Hose 2	Booster pump rpm	System Flow
(1.8 bar) 20%		7.48	7.54	0.52	2.06	2.06		2.58	2.60	2.45	2.19	2.19	2971	19.7
(3 bar) 50%		7.16	7.23	0.60	2.41	2.41		3.64	3.66	3.33	2.97	2.97	2971	19.8
(4.2 bar) 80%		6.87	6.94	0.68	2.72	2.72		4.71	4.73	4.23	3.77	3.77	2971	19.9

APPENDIX B2 – PIPING AND INSTRUMENTATION DIAGRAM OF BPS



APPENDIX B3 – BOOSTER PUMP STATION

The temperature and performance data of the booster pump station initiative has been evaluated for 13 months to analyse the sustainability and performance of the initiative. Due to the number of pumps available in the pumping stations, the mine operates on priorities between pumps to reduce maintenance costs. Due to the switching between pumps to divide the load between pumps, sometimes a pump can be in resting phase for more than a month. This makes it pointless to include each pumps graph for each month. The graphs shown are the only graphs with significant data. The performance and temperature graphs for the period August 2015 up and till August 2016 can be seen underneath:

August 2015:

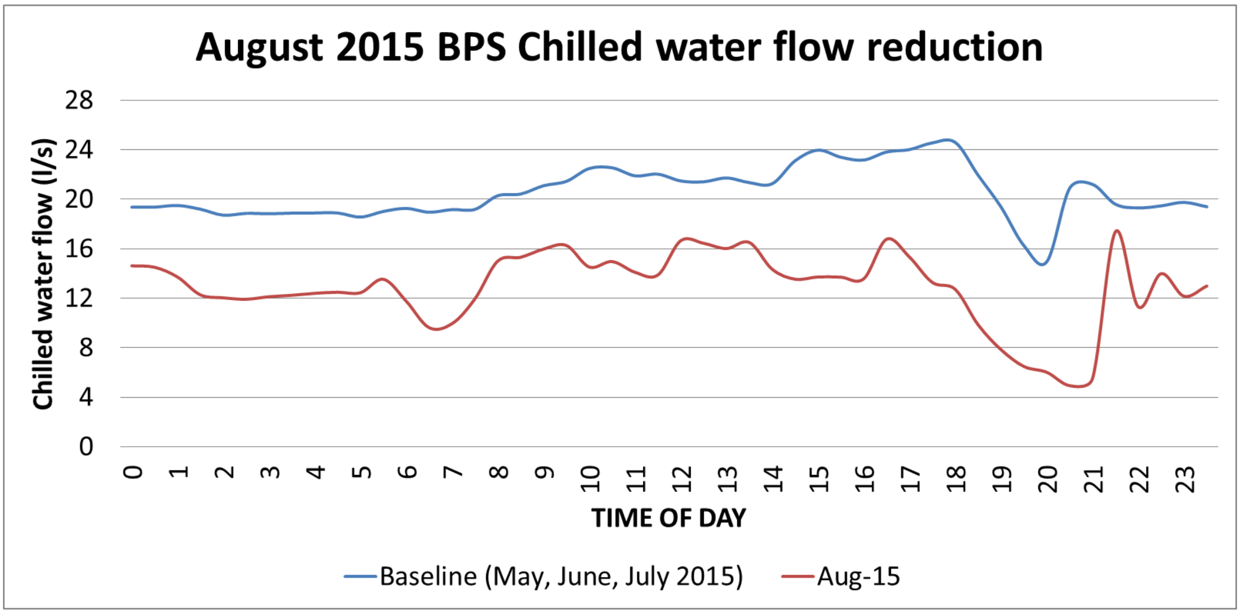


Figure 80 – BPS Aug 2015 Performance

No temperature data available.

September 2015:

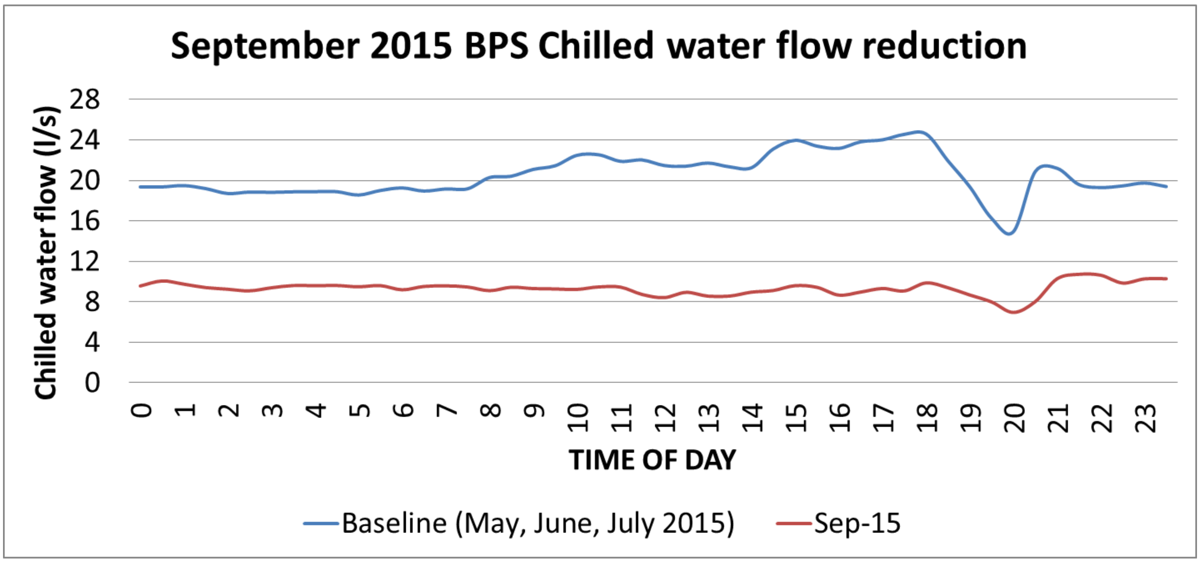


Figure 81 – BPS Sept 2015 Performance

No temperature data available.

October 2015:

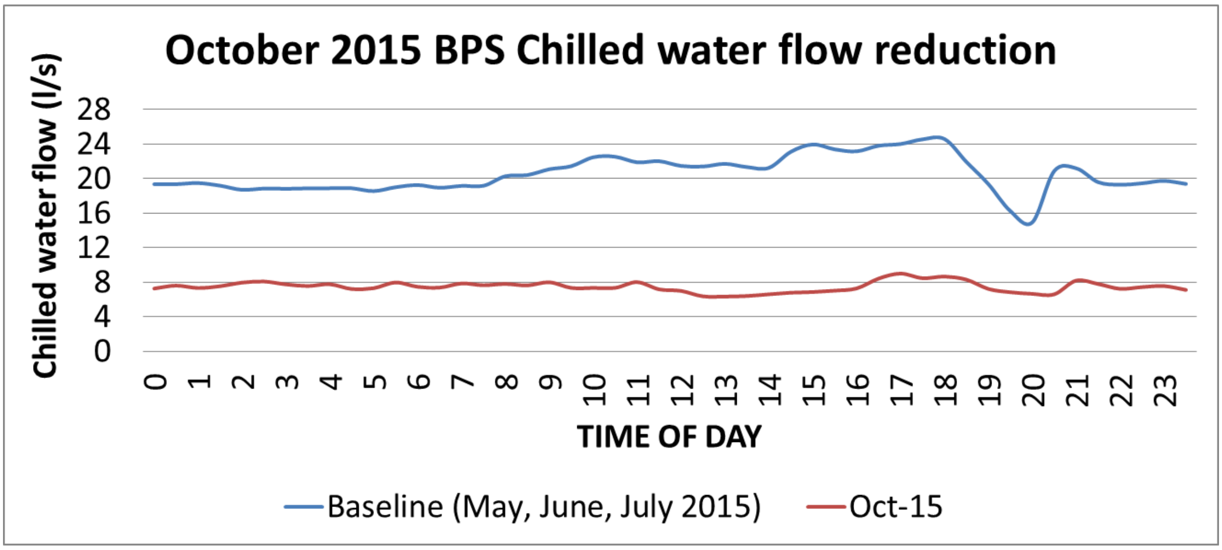


Figure 82 – BPS Oct 2015 Performance

No temperature data available.

November 2015:

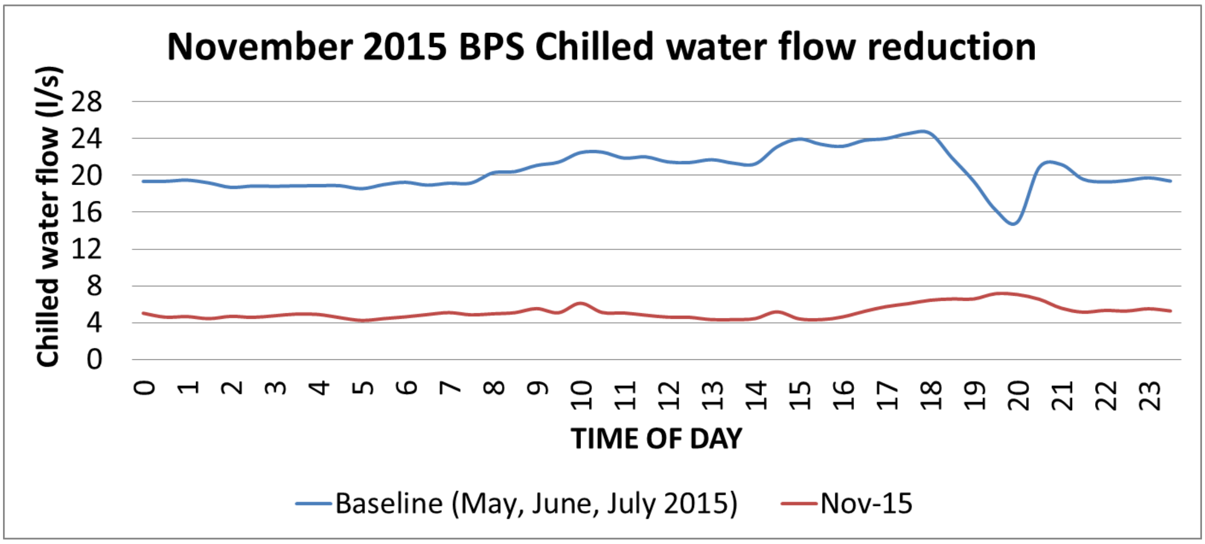


Figure 83 – BPS Nov 2015 Performance

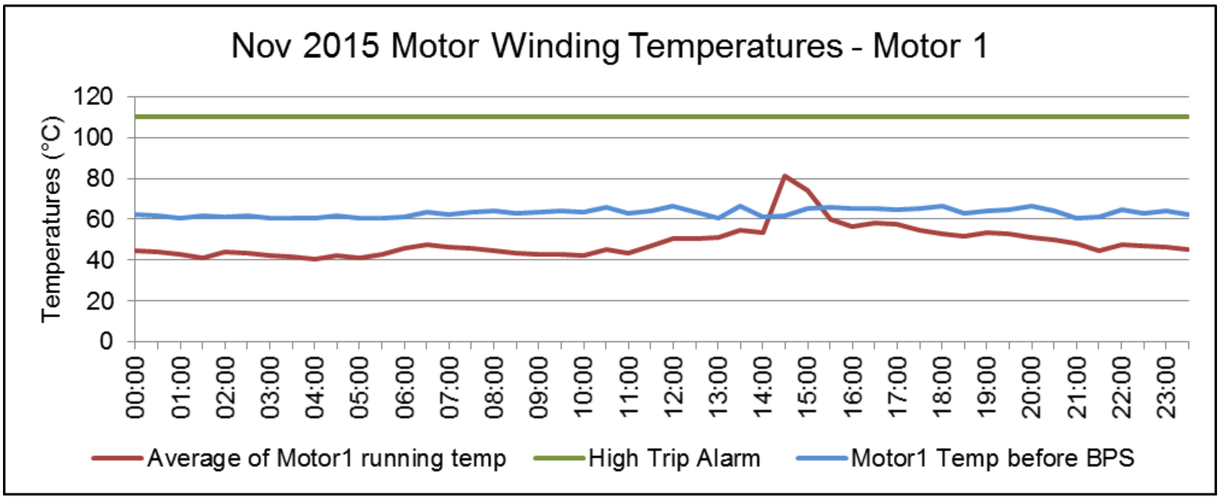


Figure 84 – BPS Nov 2015 Temperatures Motor 1

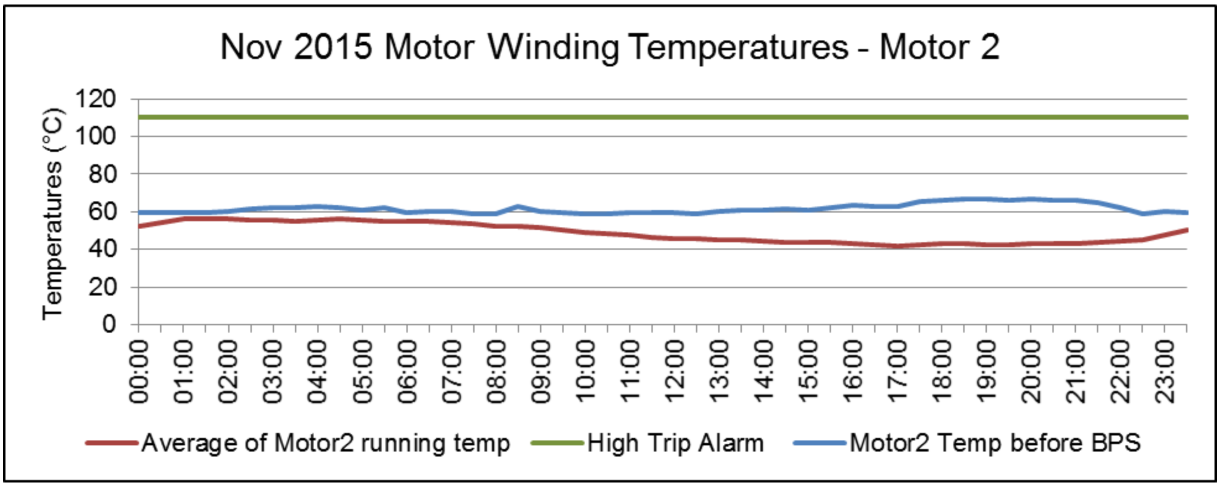


Figure 85 – BPS Nov 2015 Temperatures Motor 2

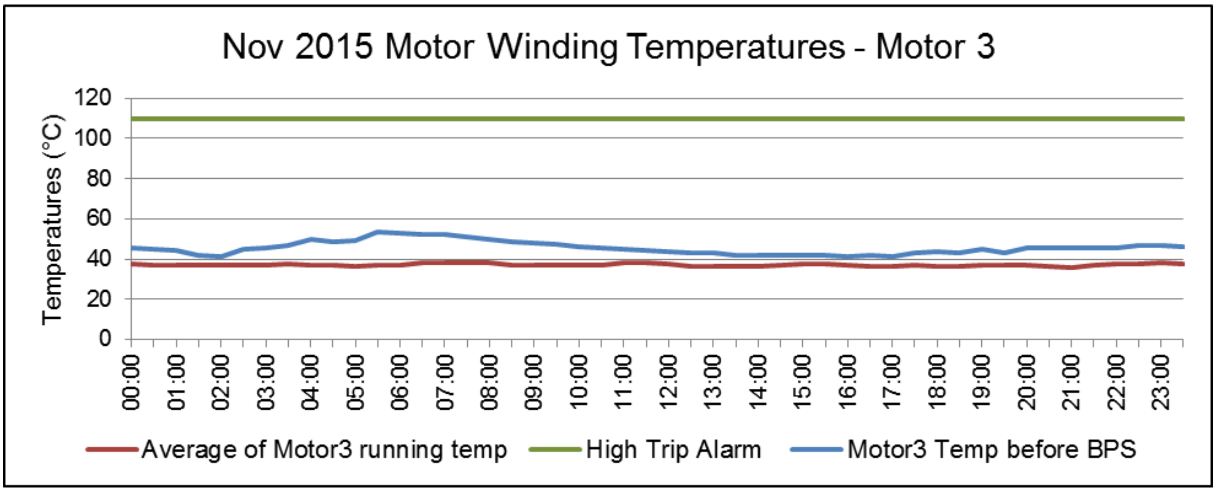


Figure 86 – BPS Nov 2015 Temperatures Motor 3

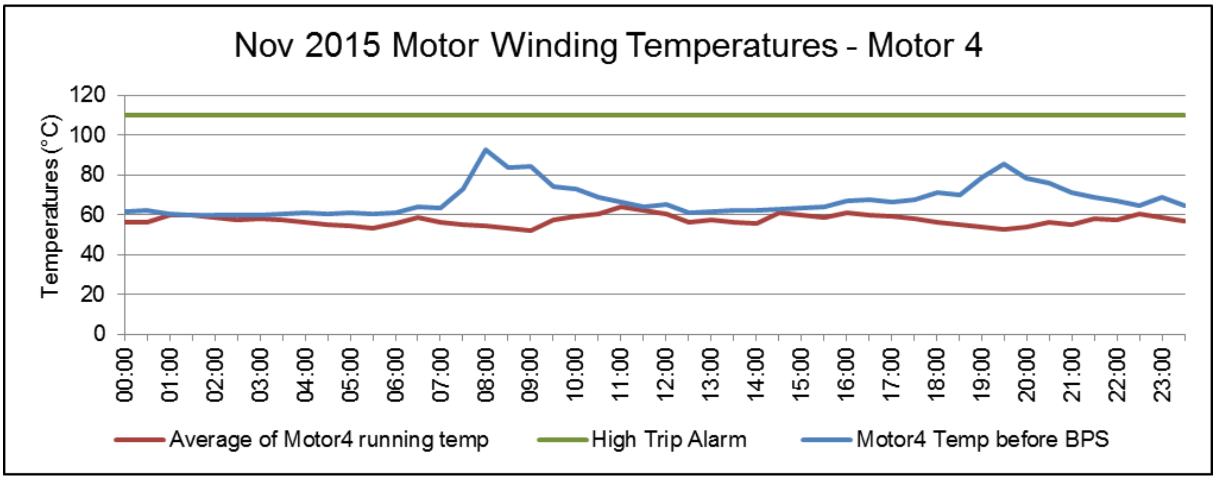


Figure 87 – BPS Nov 2015 Temperatures Motor 4

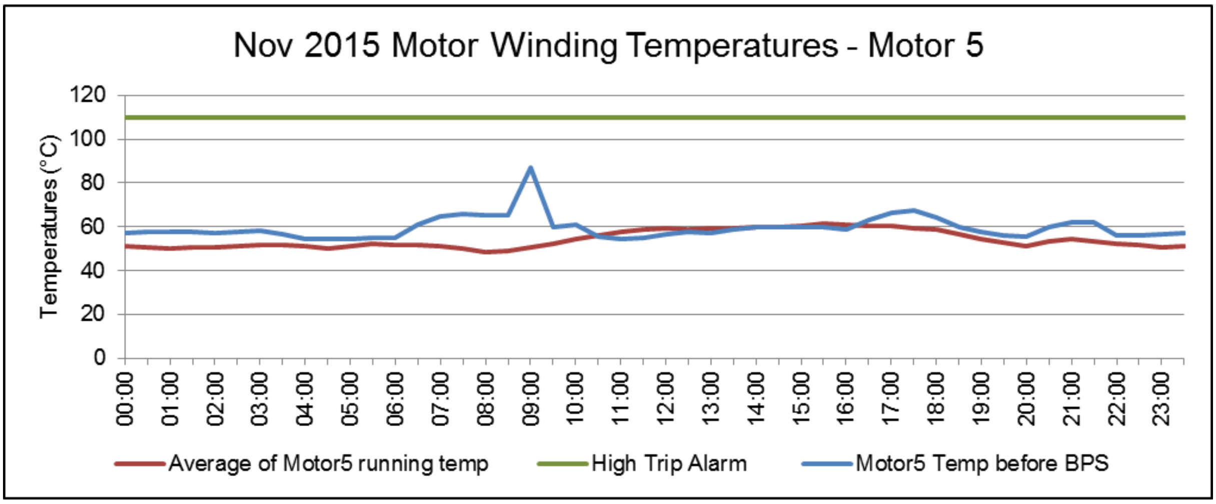


Figure 88 – BPS Nov 2015 Temperatures Motor 5

December 2015:

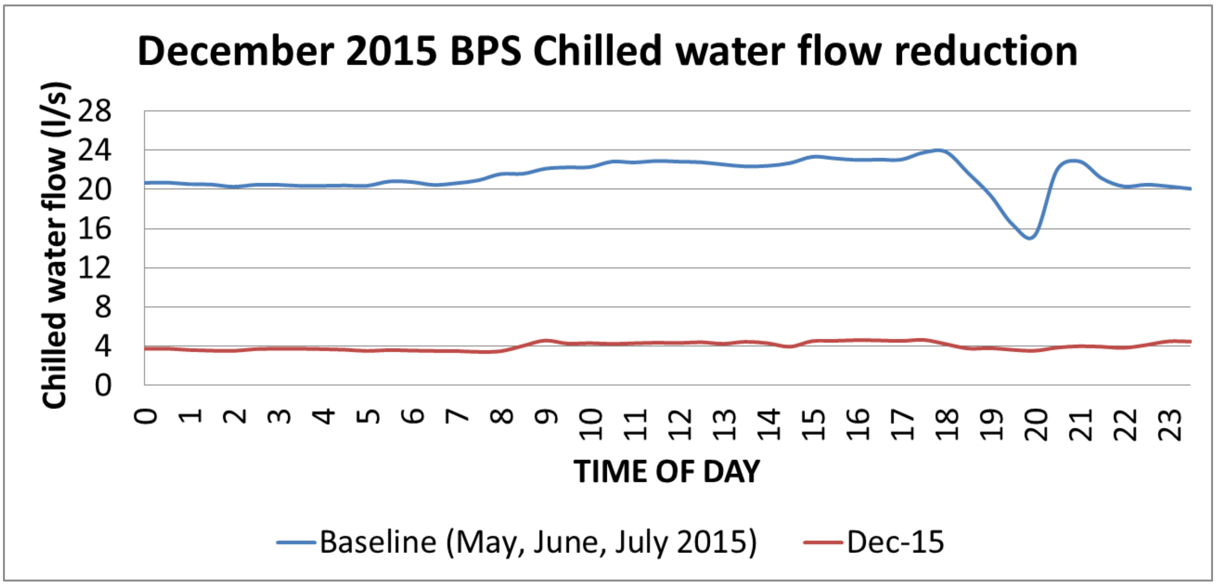


Figure 89 – BPS Dec 2015 Performance

Included from here on is the temperature of the clear water used for motor cooling.

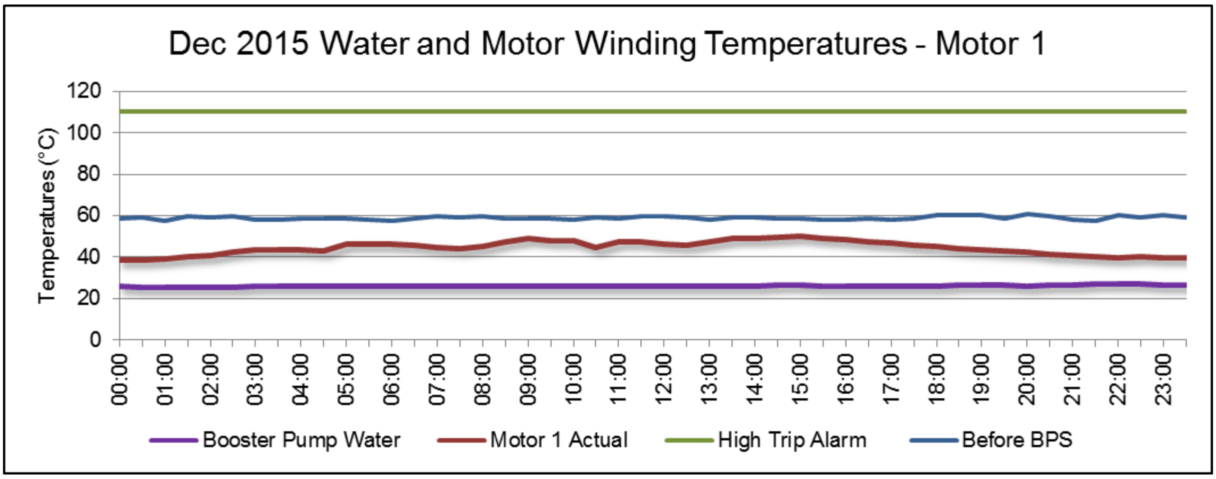


Figure 90 – BPS Dec 2015 Temperatures Motor 1

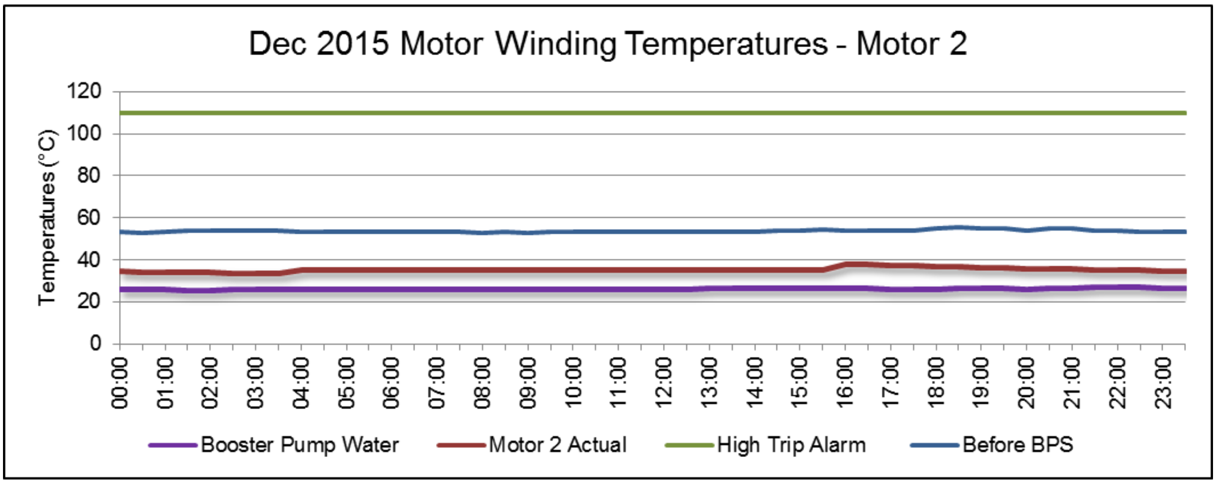


Figure 91 – BPS Dec 2015 Temperatures Motor 2

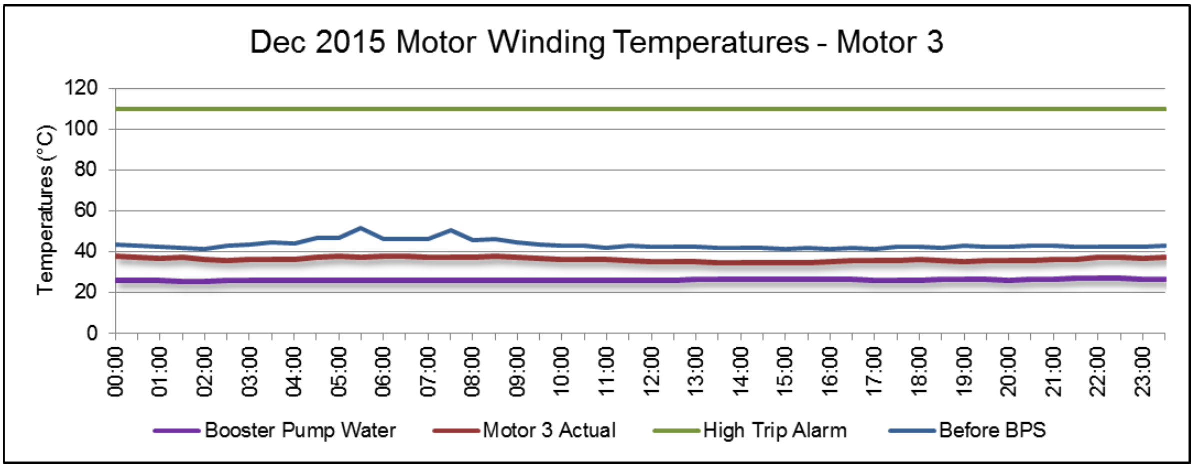


Figure 92 – BPS Dec 2015 Temperatures Motor 3

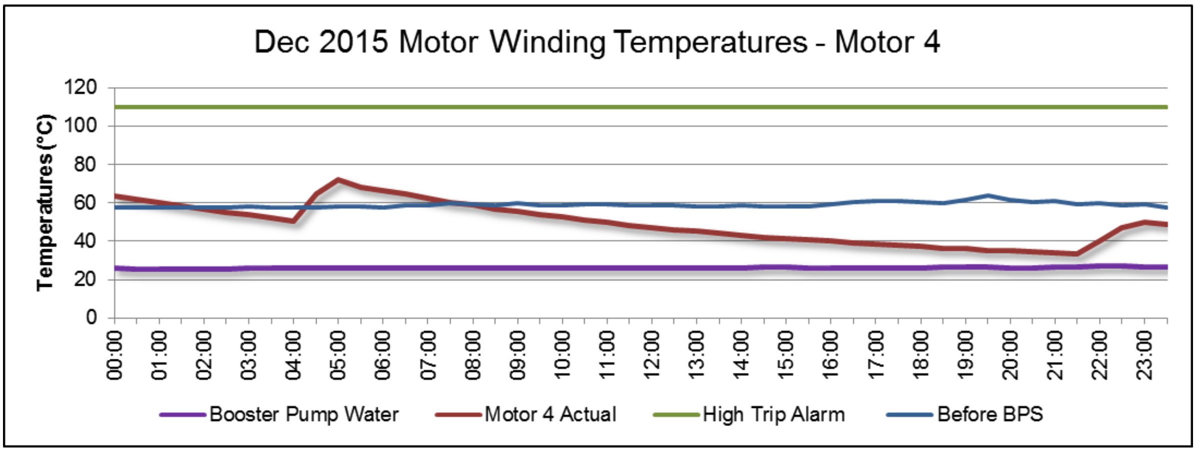


Figure 93 – BPS Dec 2015 Temperatures Motor 4

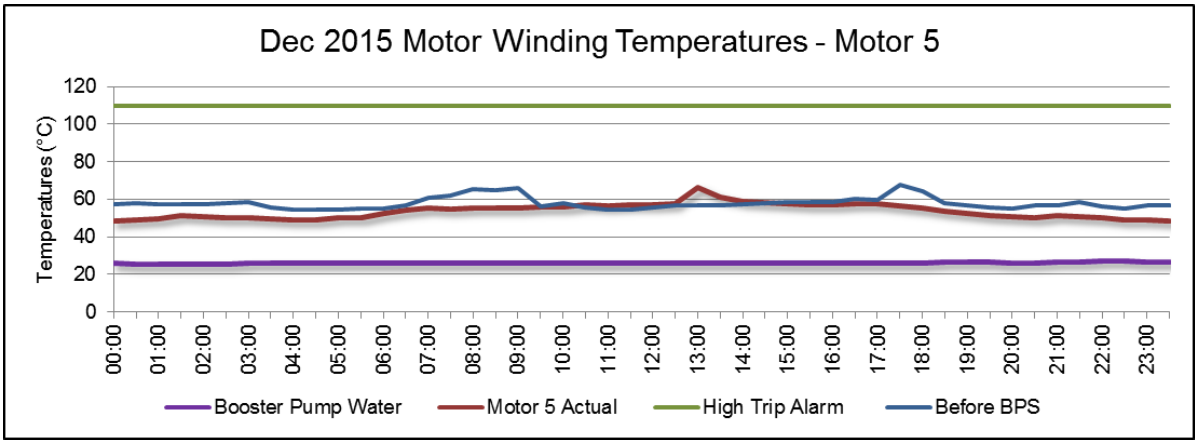


Figure 94 – BPS Dec 2015 Temperatures Motor 5

January 2016:

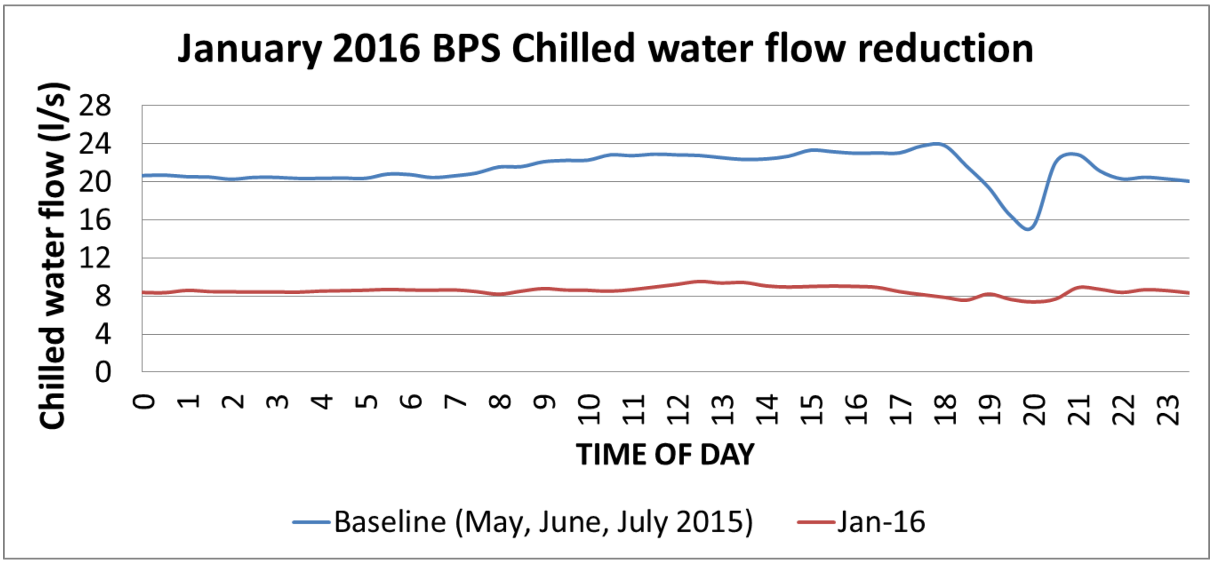


Figure 95 – BPS Jan 2016 Performance

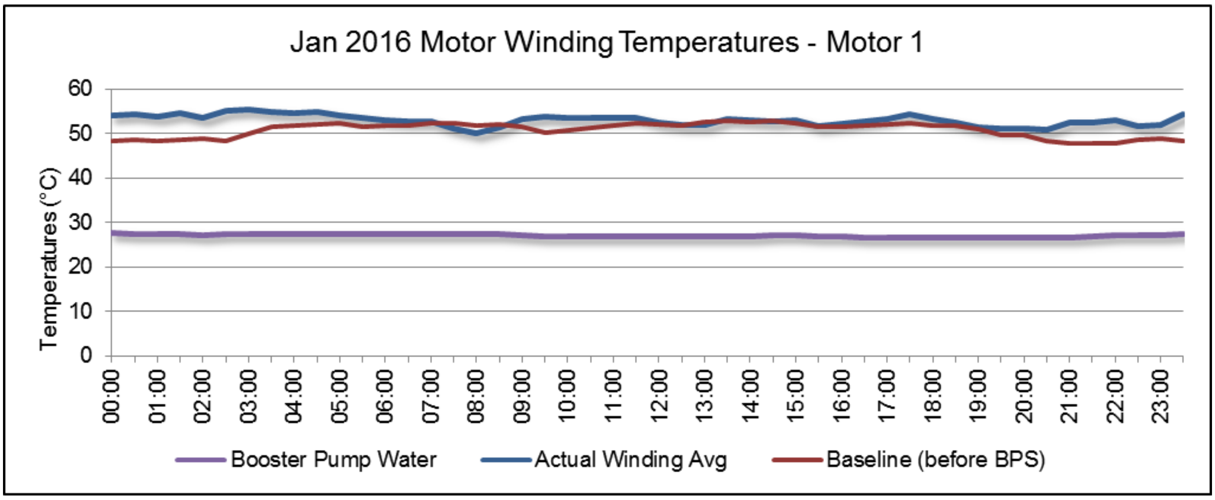


Figure 96 – BPS Jan 2016 Temperatures Motor 1

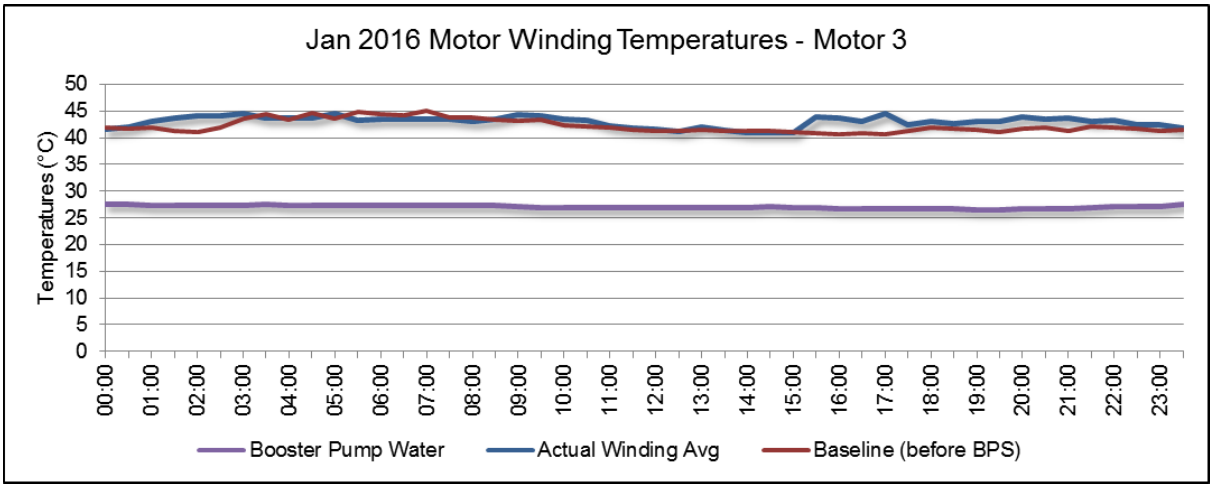


Figure 97 – BPS Jan 2016 Temperatures Motor 3

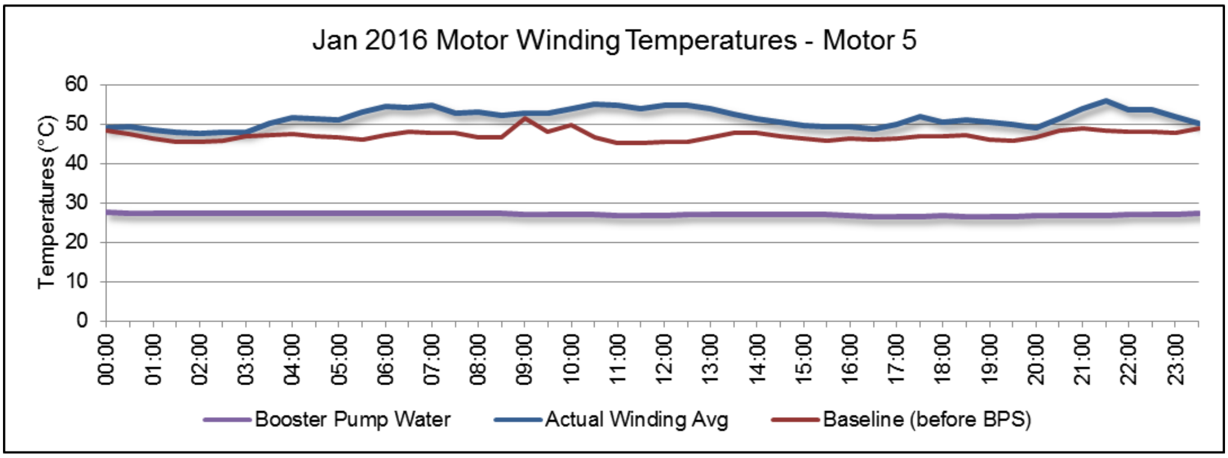


Figure 98 – BPS Jan 2016 Temperatures Motor 5

February 2016:

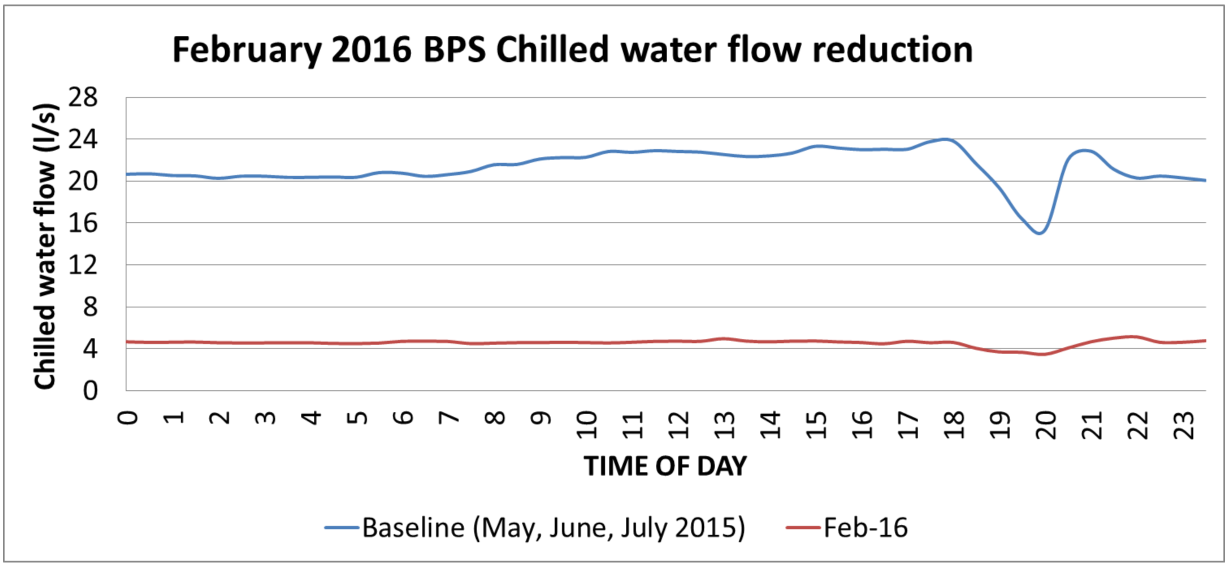


Figure 99 – BPS Feb 2016 Performance

No clear water temperature data available further.

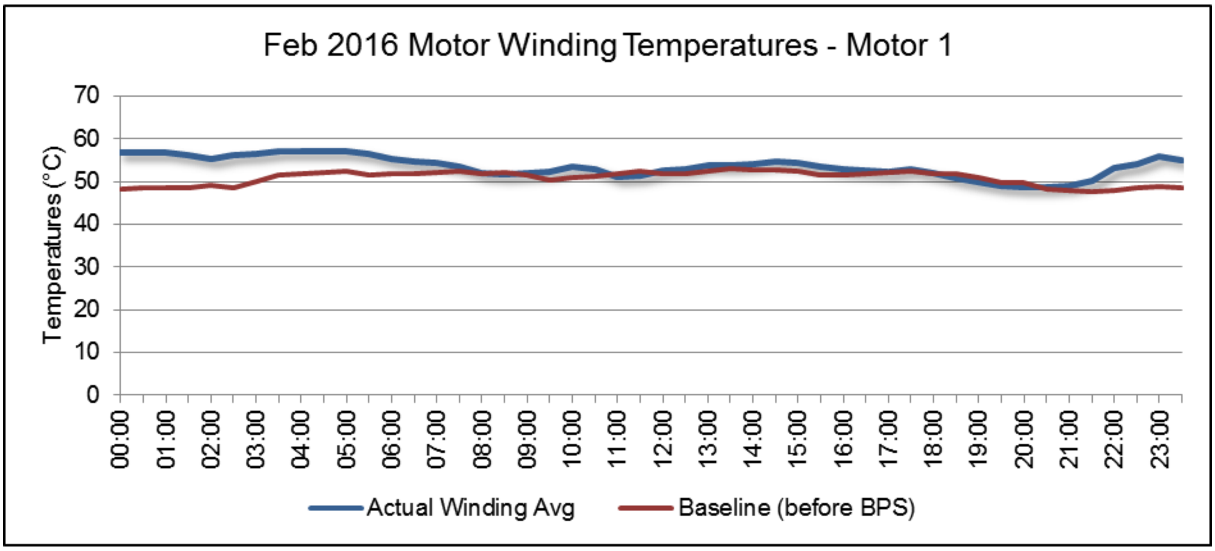


Figure 100 – BPS Feb 2016 Temperatures Motor 1

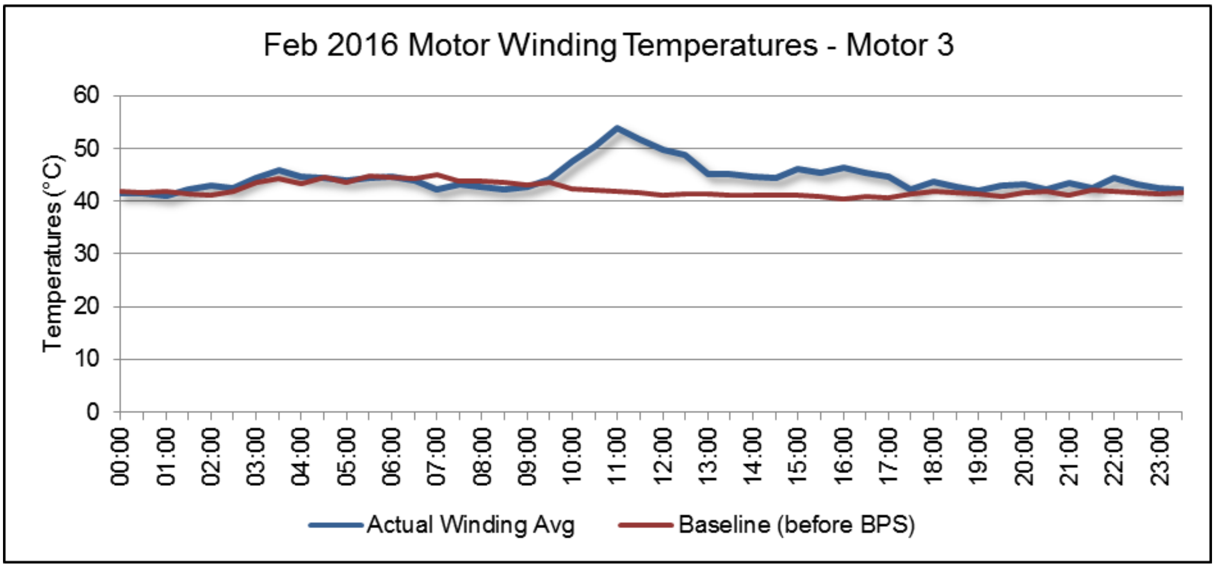


Figure 101 – BPS Feb 2016 Temperatures Motor 3

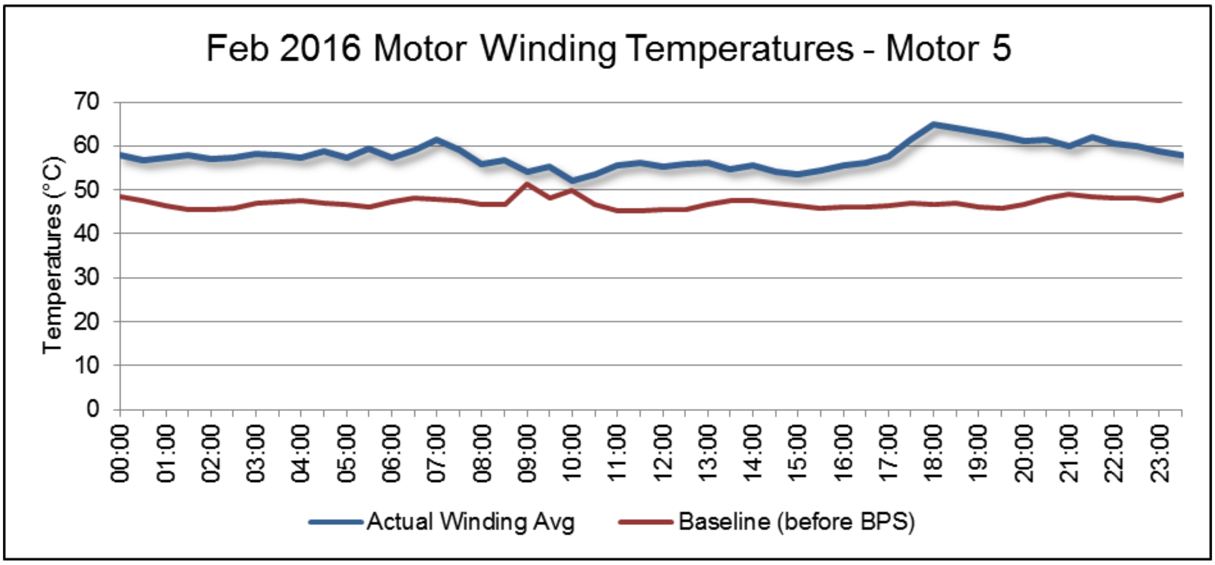


Figure 102 – BPS Feb 2016 Temperatures Motor 5

March 2016:

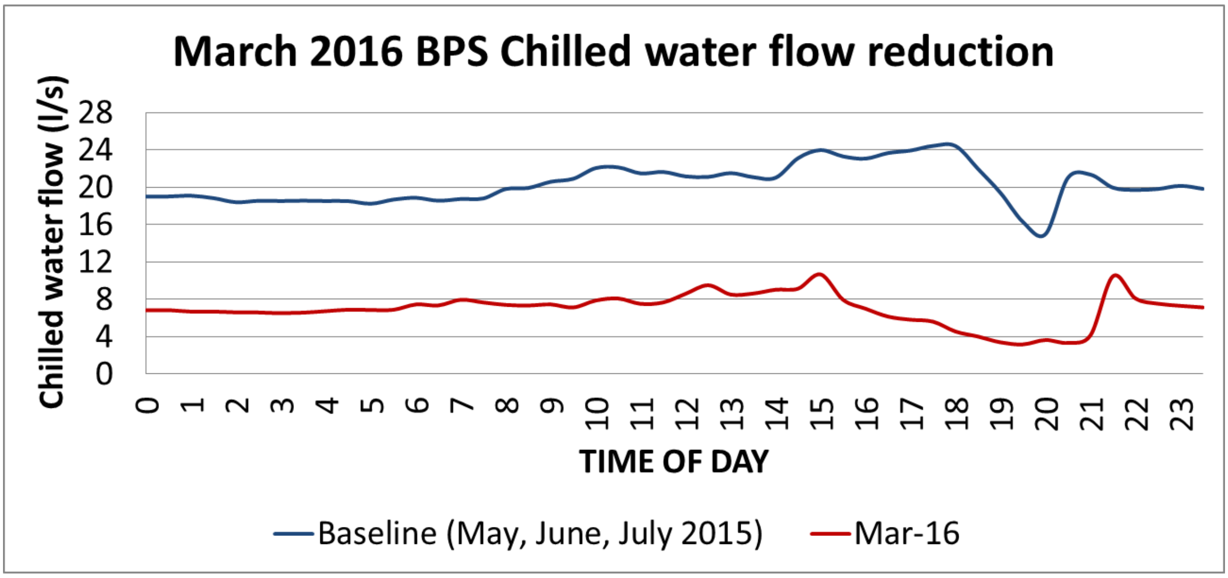


Figure 103 – BPS Mar 2016 Performance

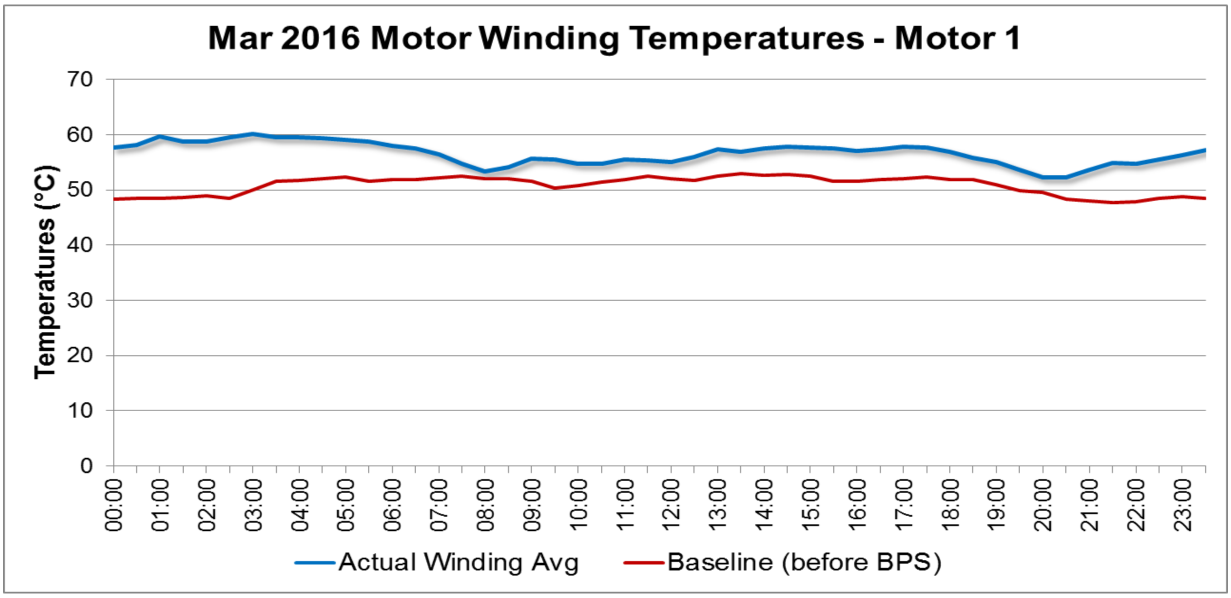


Figure 104 – BPS Mar 2016 Temperatures Motor 1

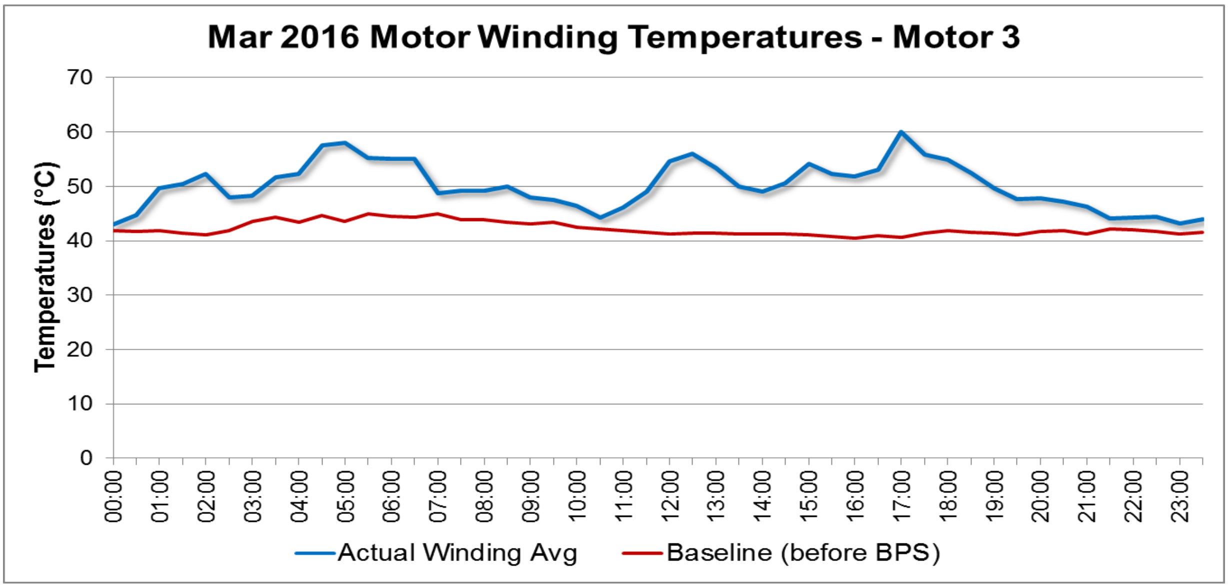


Figure 105 – BPS Mar 2016 Temperatures Motor 3

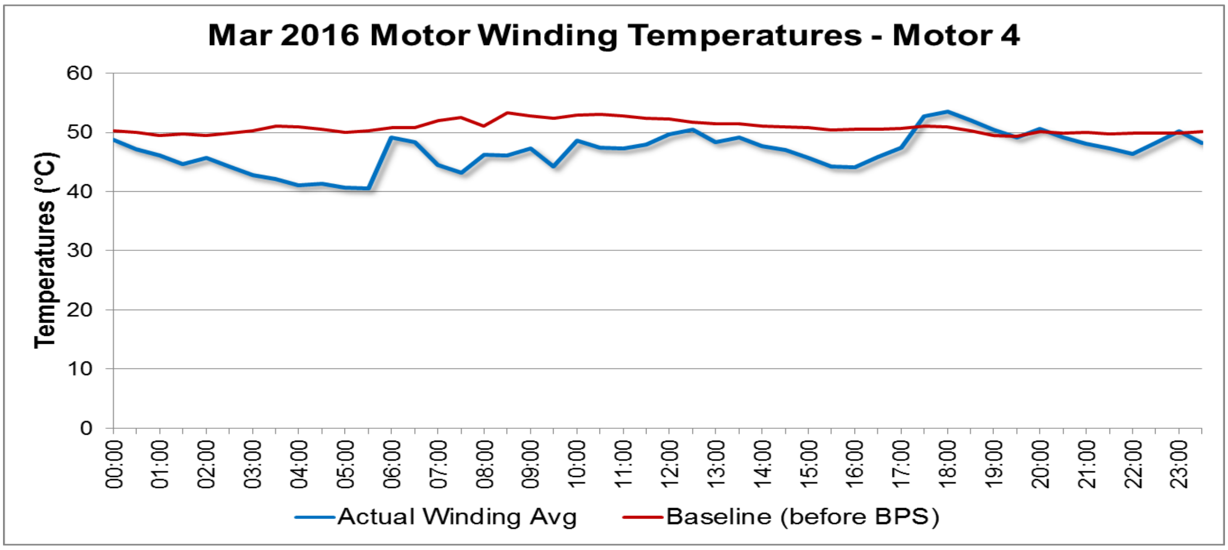


Figure 106 – BPS Mar 2016 Temperatures Motor 4

April 2016:

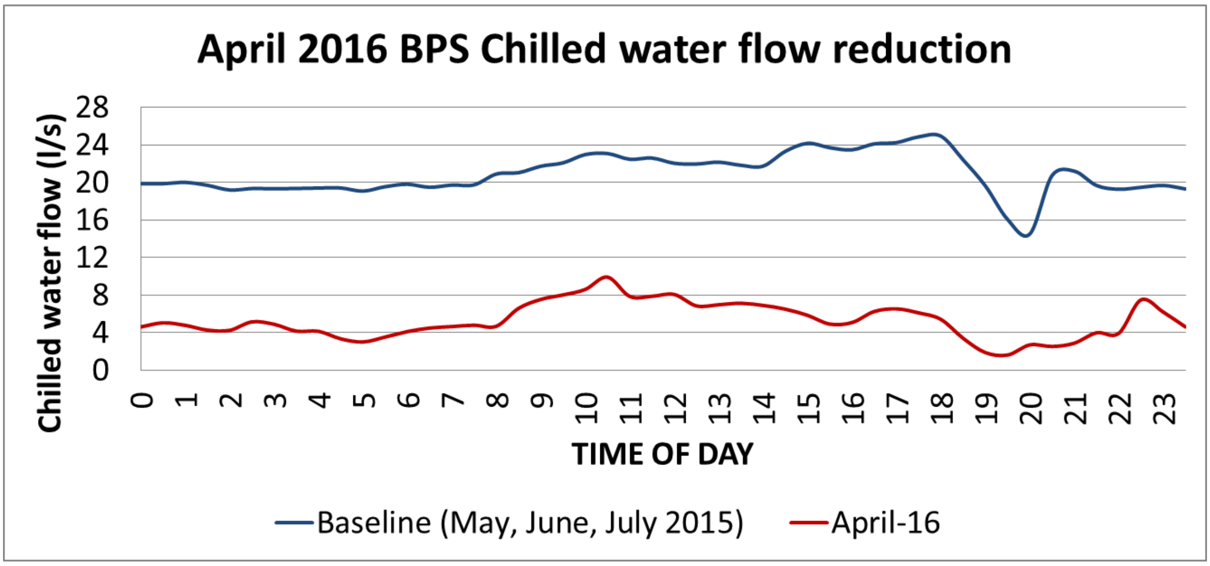


Figure 107 – BPS Apr 2016 Performance

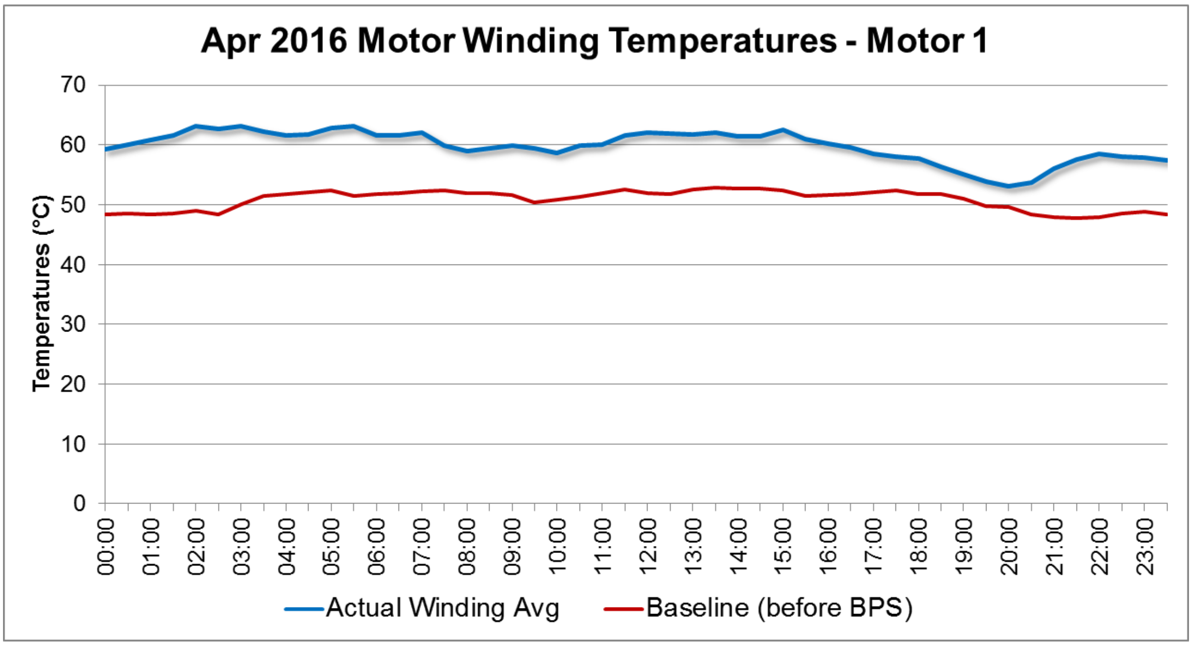


Figure 108 – BPS Apr 2016 Temperature Motor 1

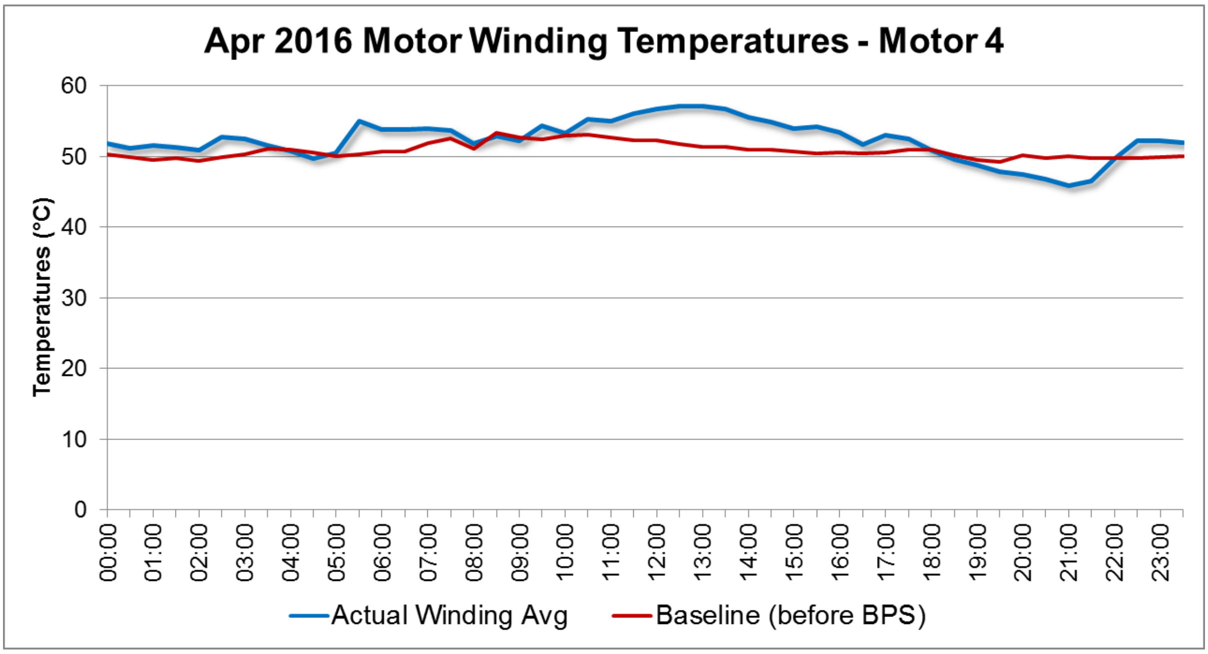


Figure 109 – BPS Apr 2016 Temperature Motor 4

May 2016:

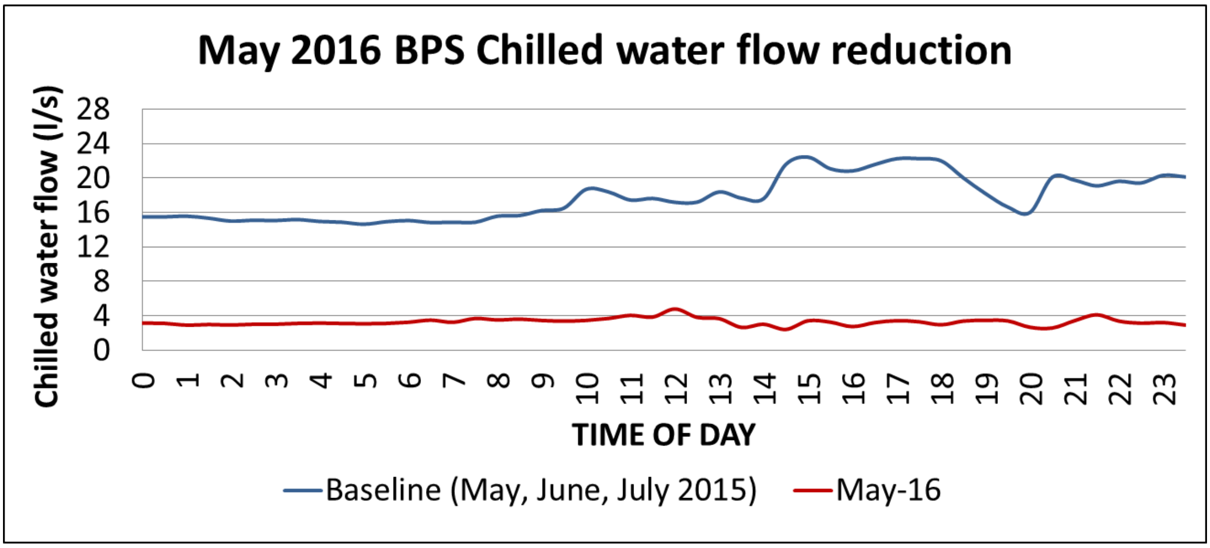


Figure 110 – BPS May 2016 Performance

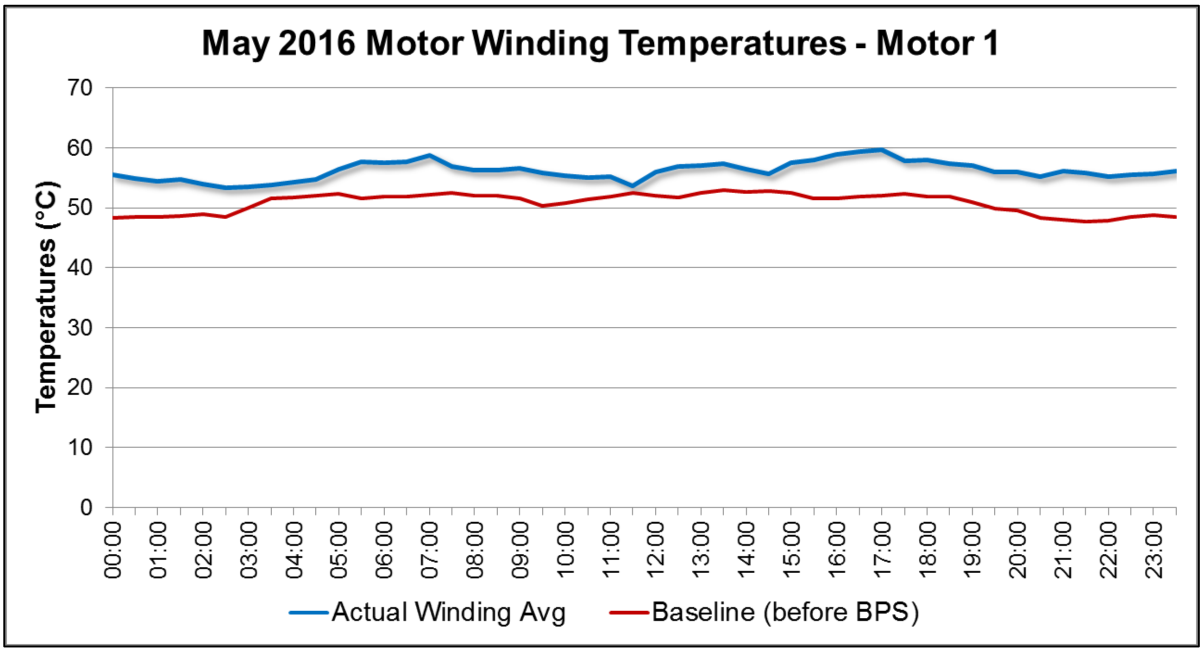


Figure 111 – BPS May 2016 Temperatures Motor 1

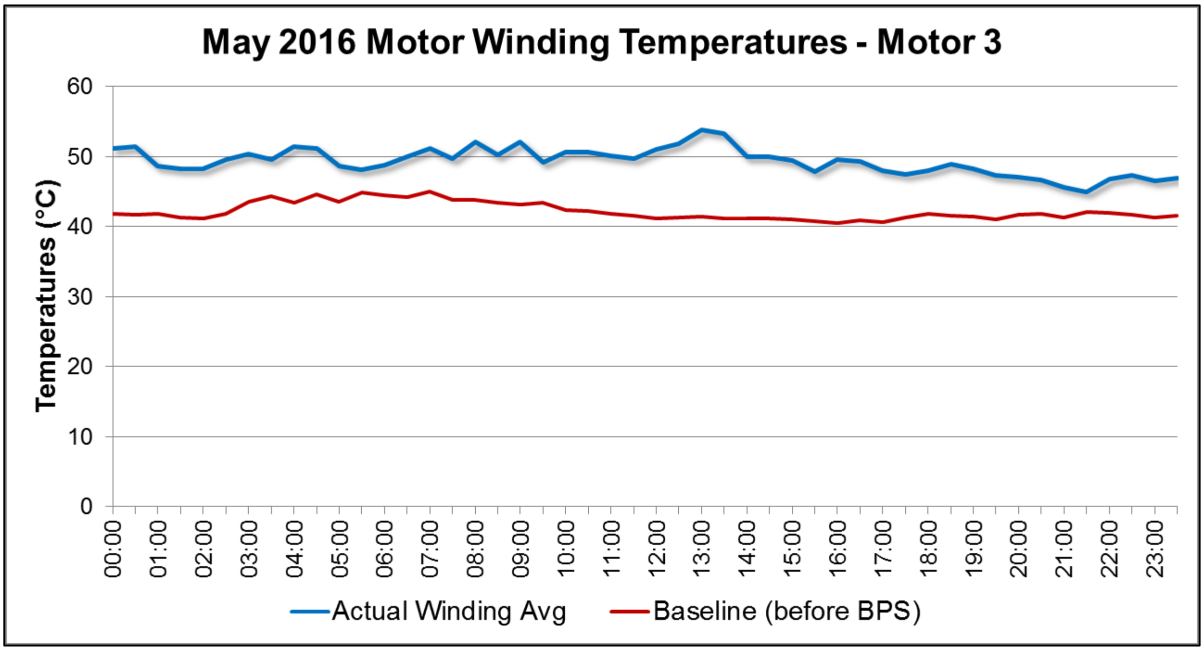


Figure 112 – BPS May 2016 Temperatures Motor 3

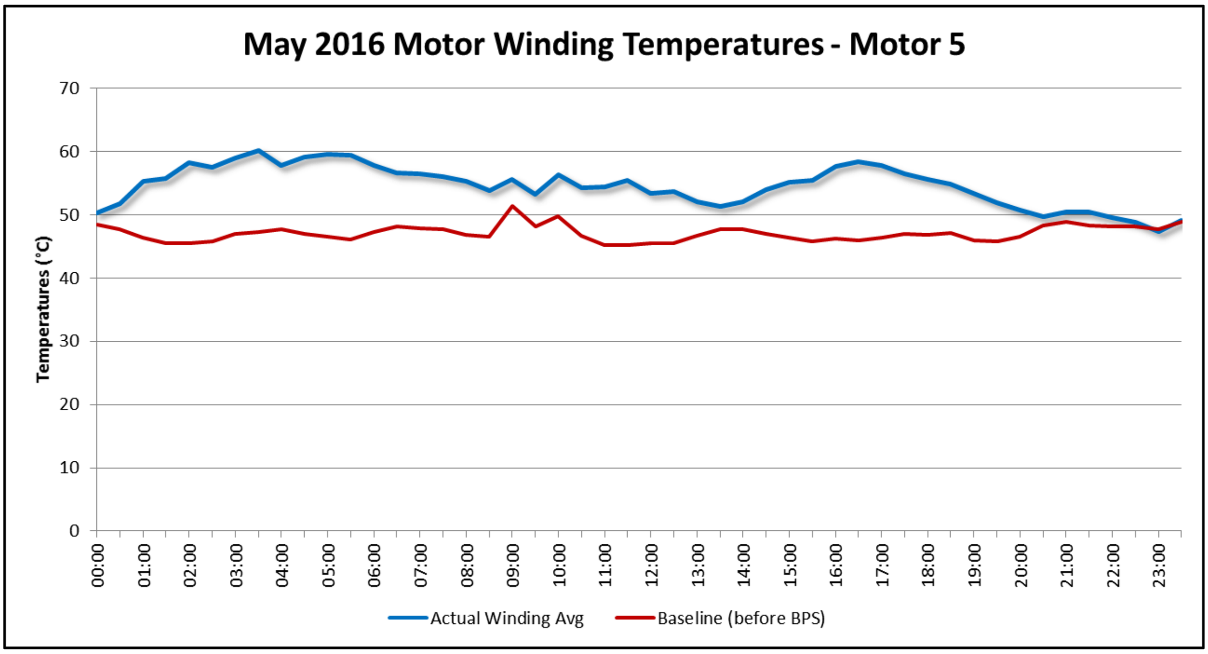


Figure 113 – BPS May 2016 Temperatures Motor 5

June 2016:

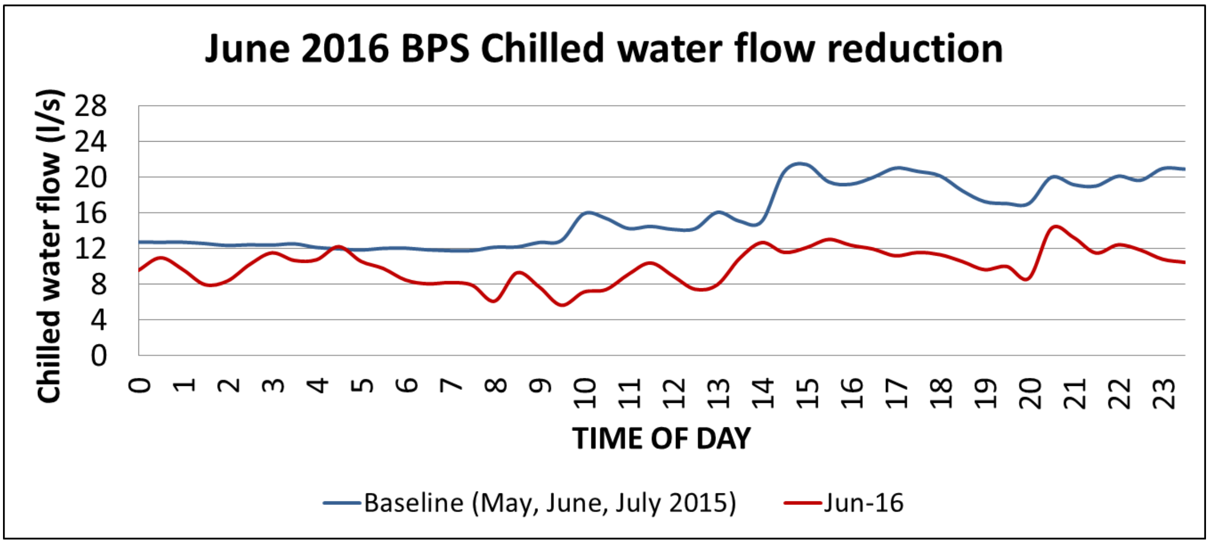


Figure 114 – BPS Jun 2016 Performance

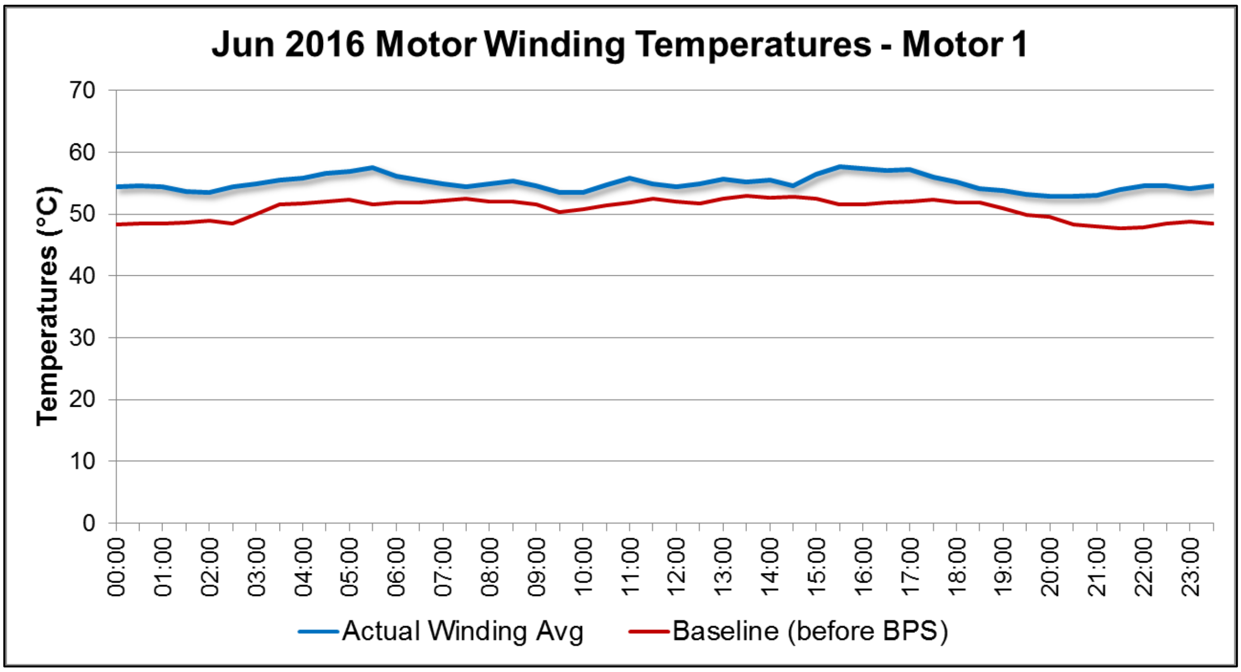


Figure 115 – BPS Jun 2016 Temperatures Motor 1

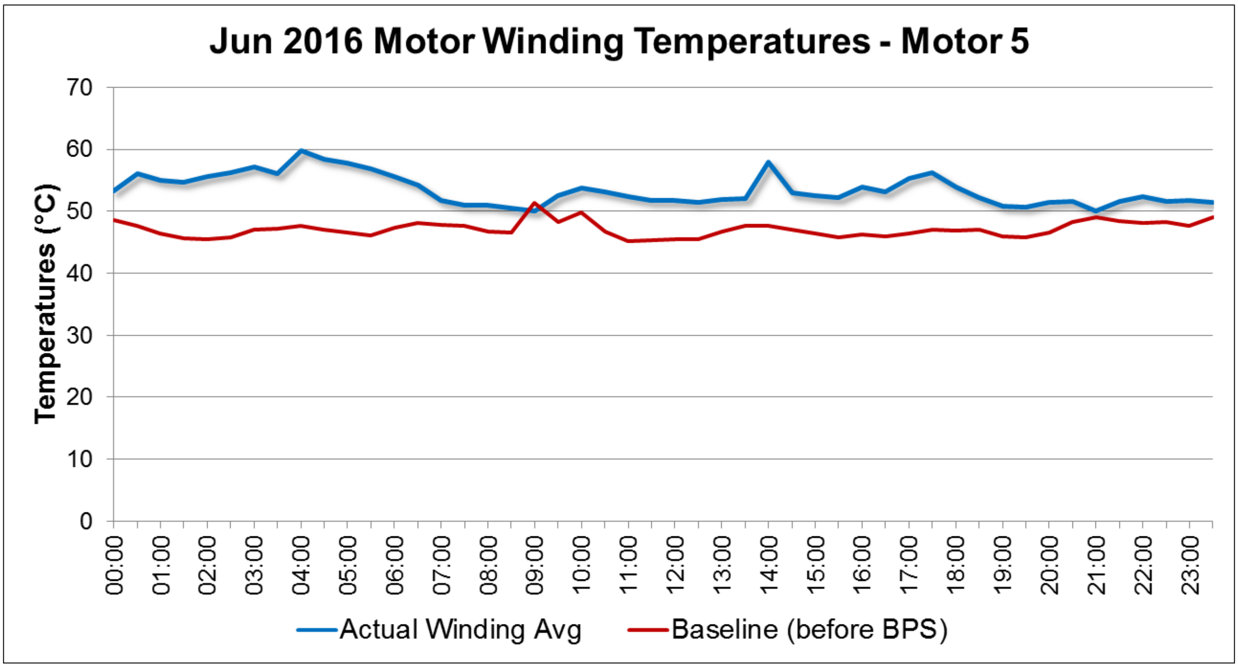


Figure 116 – BPS Jun 2016 Temperatures Motor 5

July 2016:

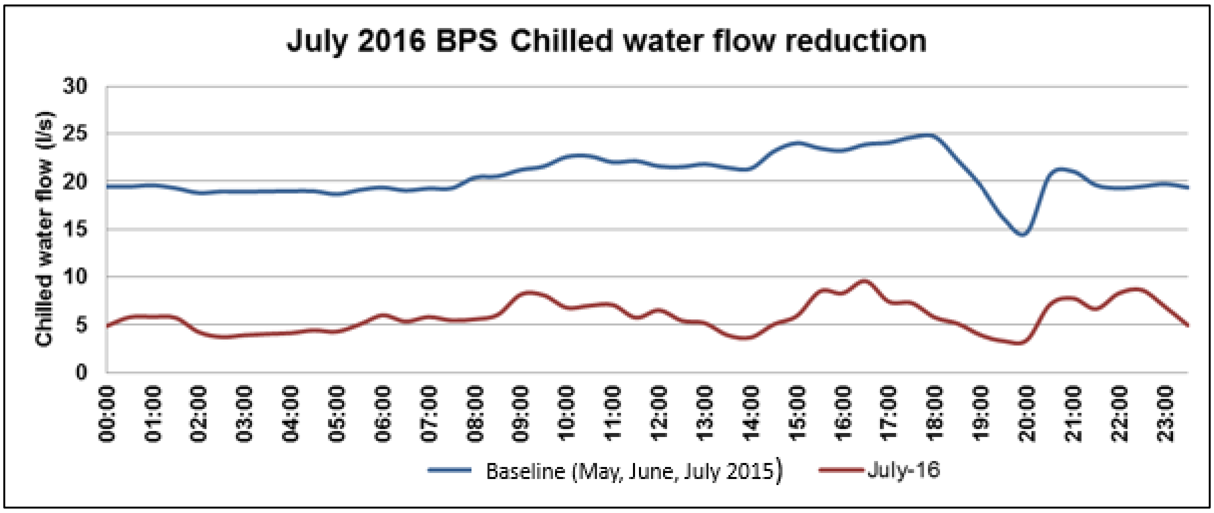


Figure 117 – BPS Jul 2016 Performance

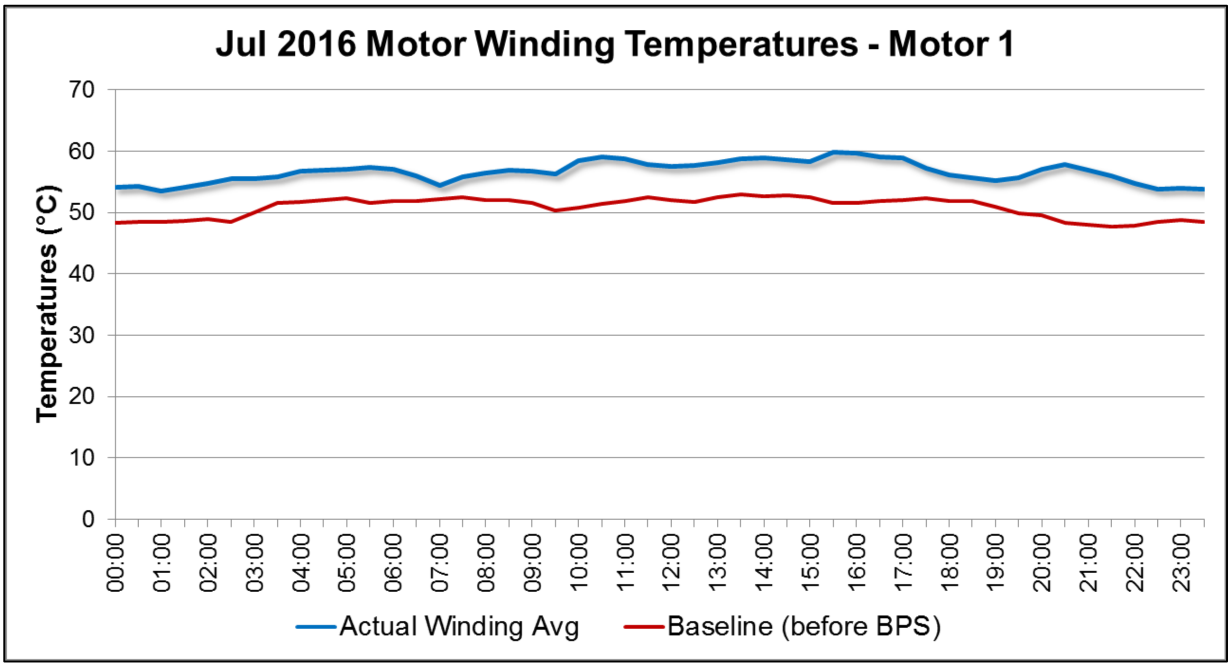


Figure 118 – BPS Jul 2016 Temperatures Motor 1

August 2016:

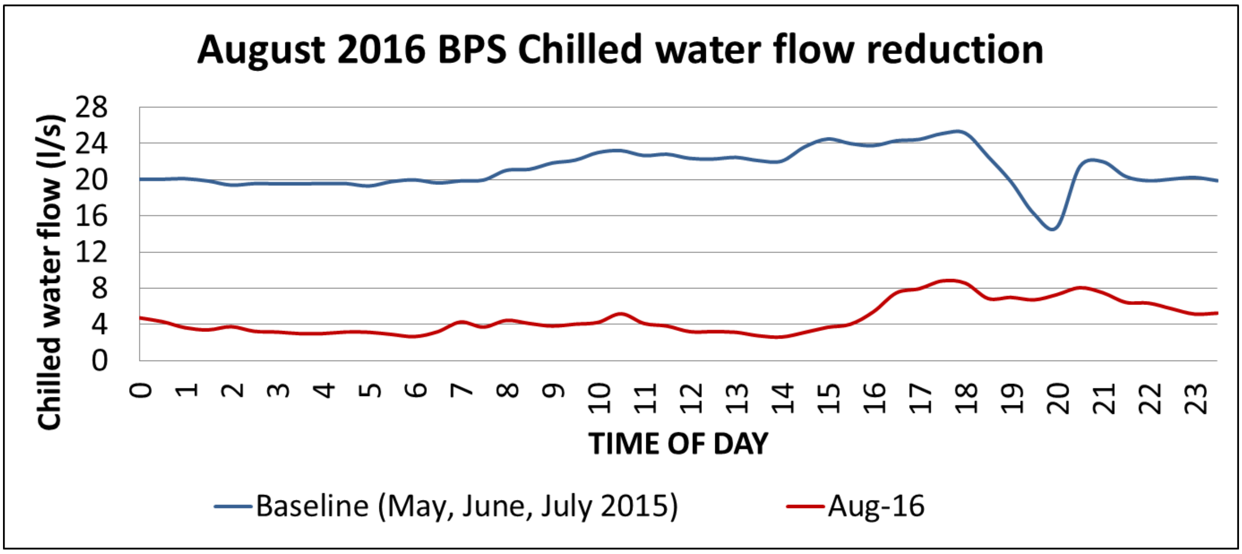


Figure 119 – BPS Aug 2016 Performance

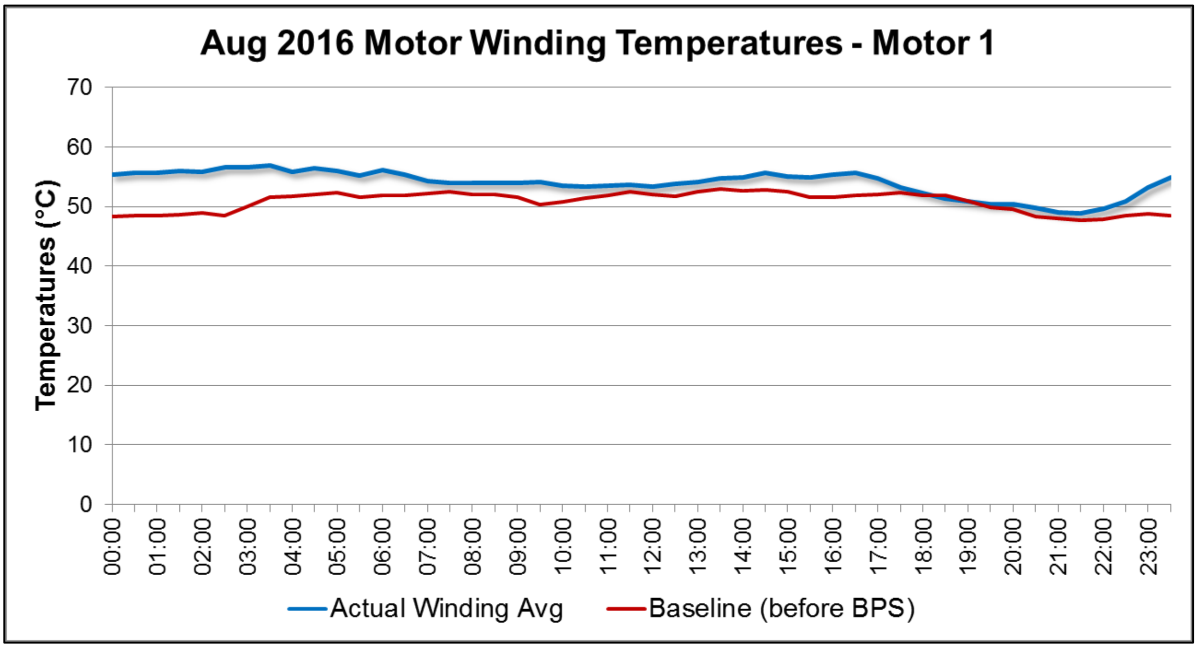


Figure 120 – BPS Aug 2016 Temperatures Motor 1

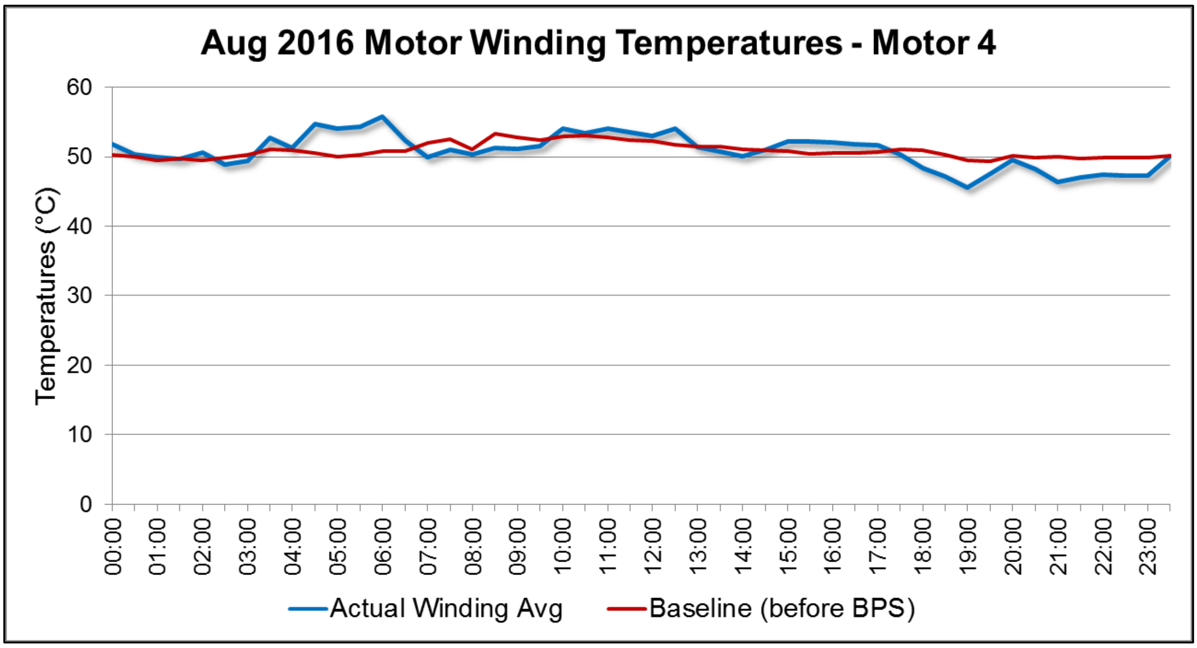


Figure 121 – BPS Aug 2016 Temperatures Motor 4

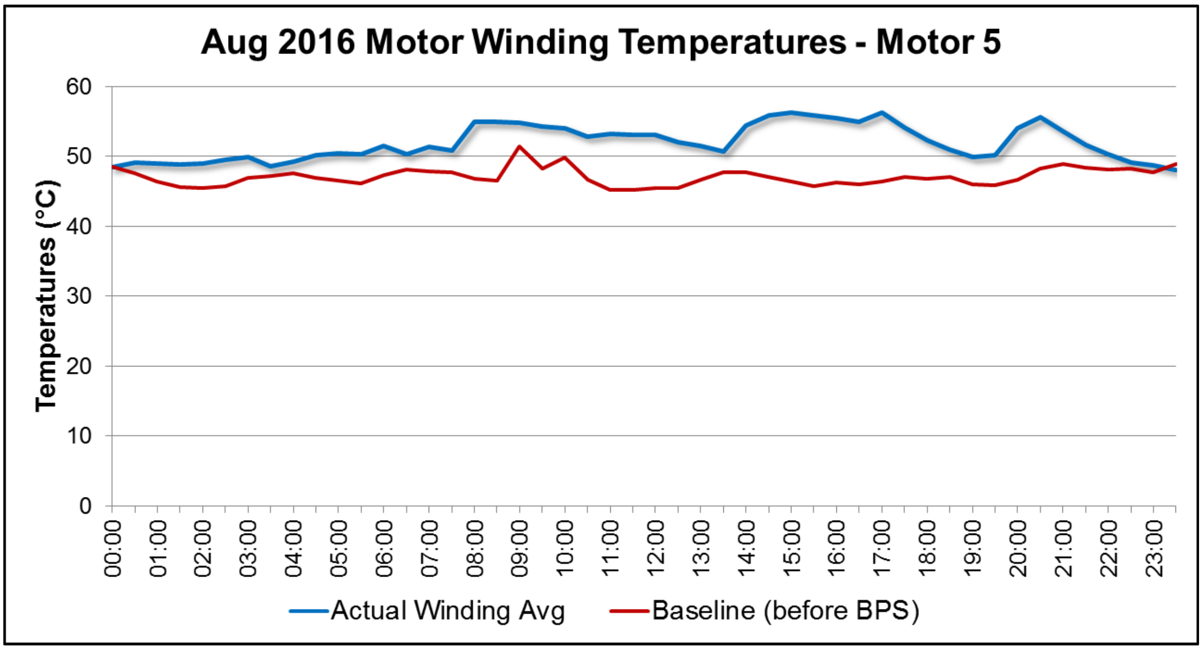


Figure 122 – BPS Aug 2016 Temperatures Motor 5

APPENDIX C – AUTOMATED SOLENOID VALVES

The temperature and performance data of the automated solenoid valves initiative has been evaluated for a 10 month period to analyse the sustainability and performance of the initiative. September 2015 was used as the baseline period. The graphs for the period November 2015 up and till August 2016 can be seen underneath:

November 2015:

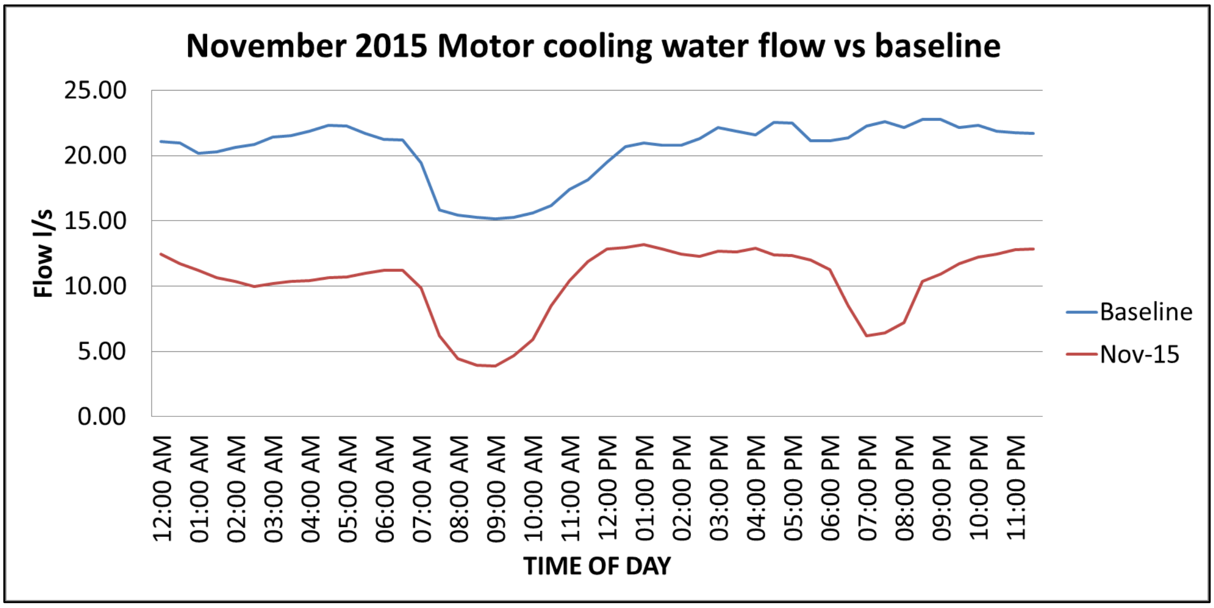


Figure 123 – Auto Solenoids Nov 2015 Performance

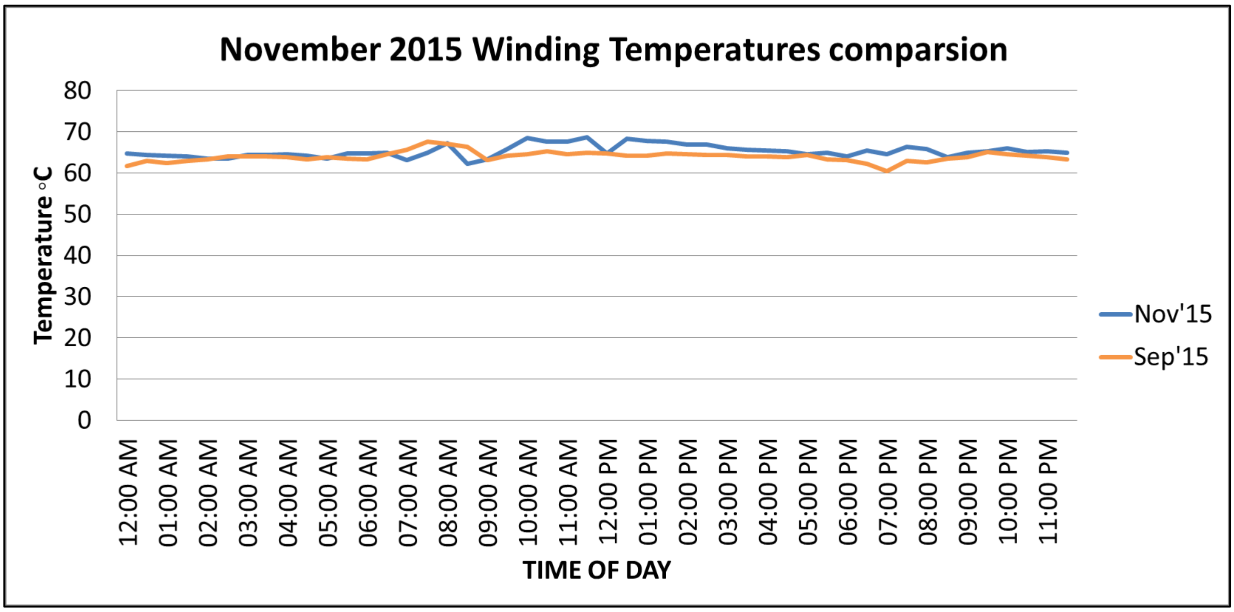


Figure 124 – Auto Solenoids Nov 2015 Winding Temperatures

December 2015:

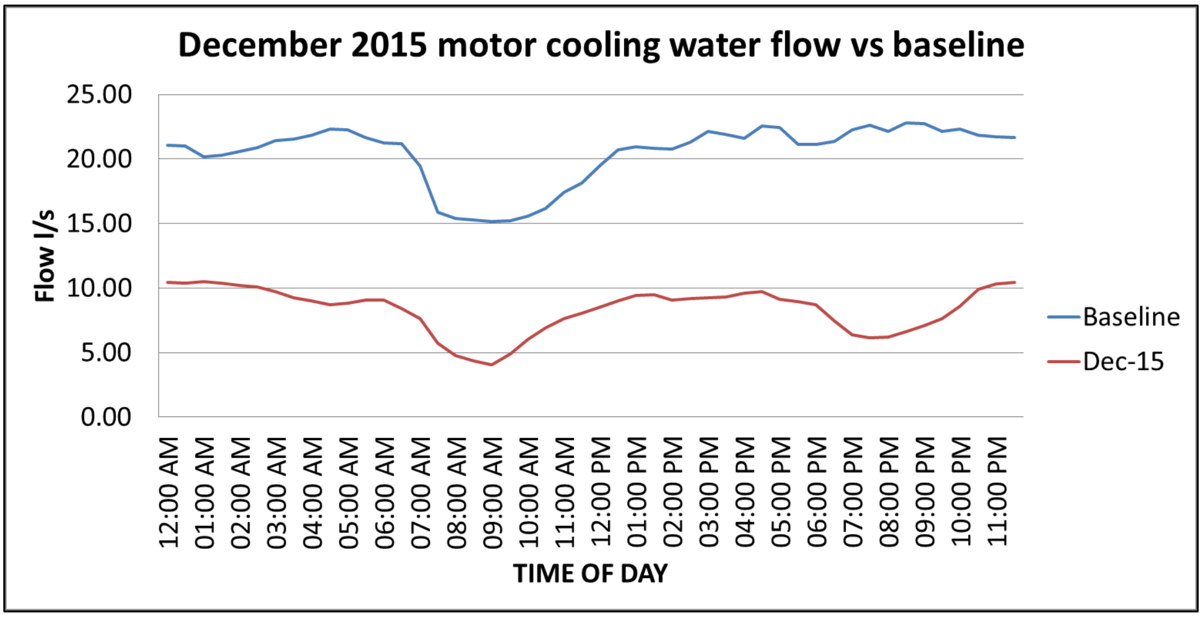


Figure 125 – Auto Solenoids Dec 2015 Performance

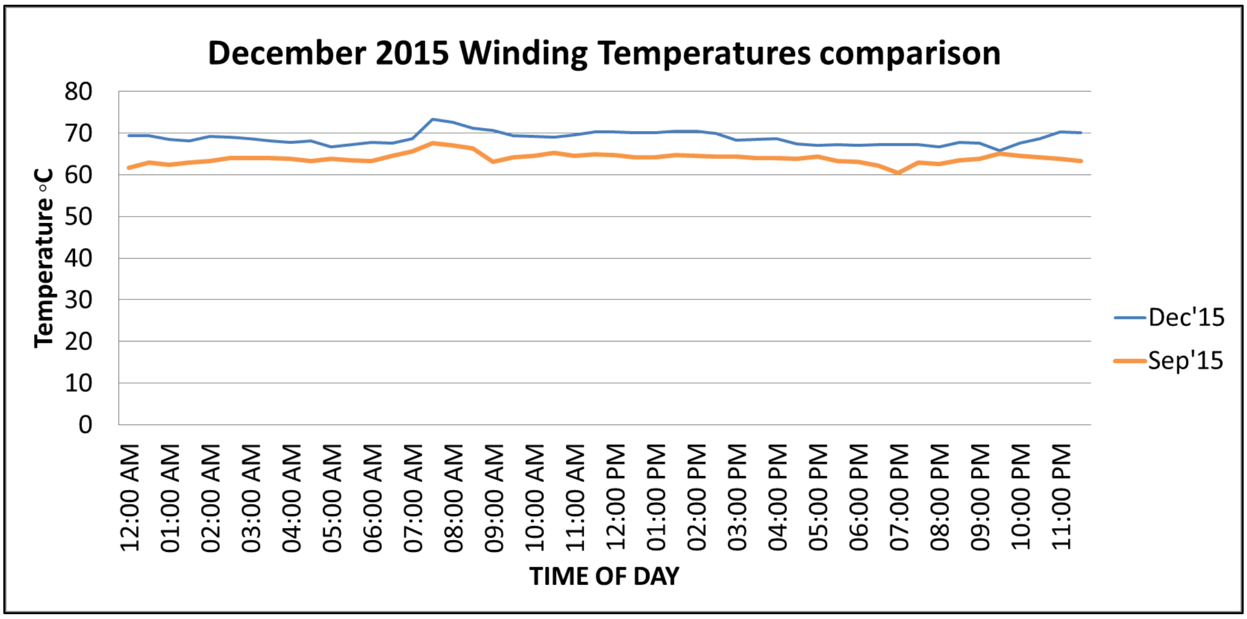


Figure 126 – Auto Solenoids Dec 2015 Winding Temperatures

January 2016:

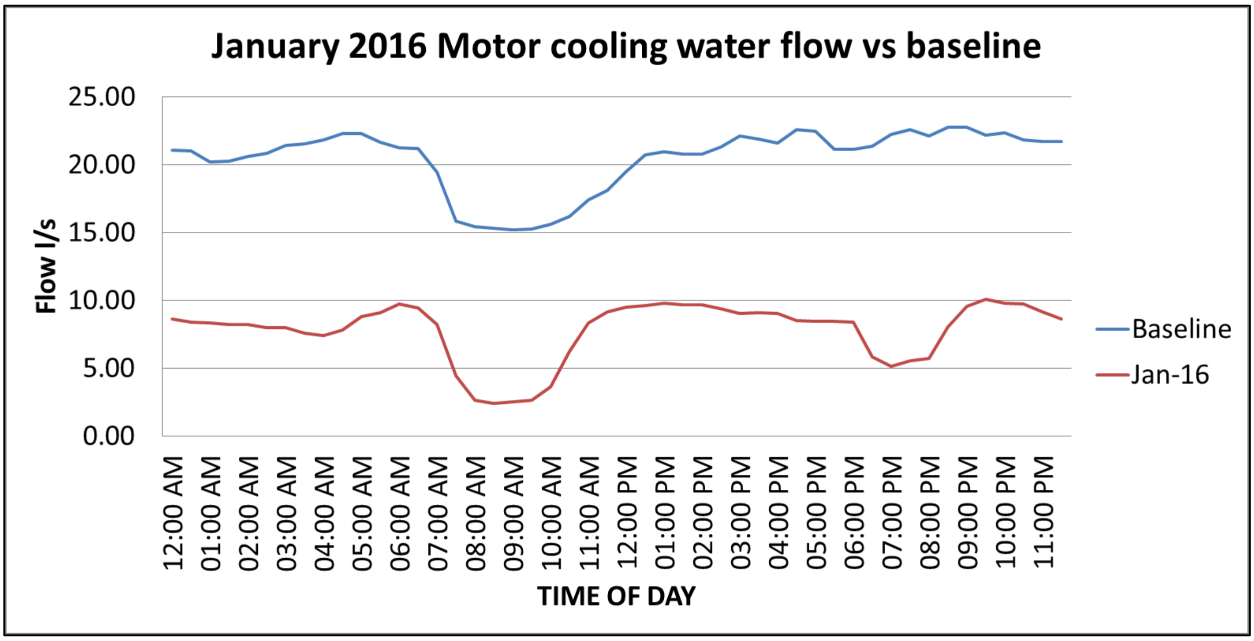


Figure 127 – Auto Solenoids Jan 2016 Performance

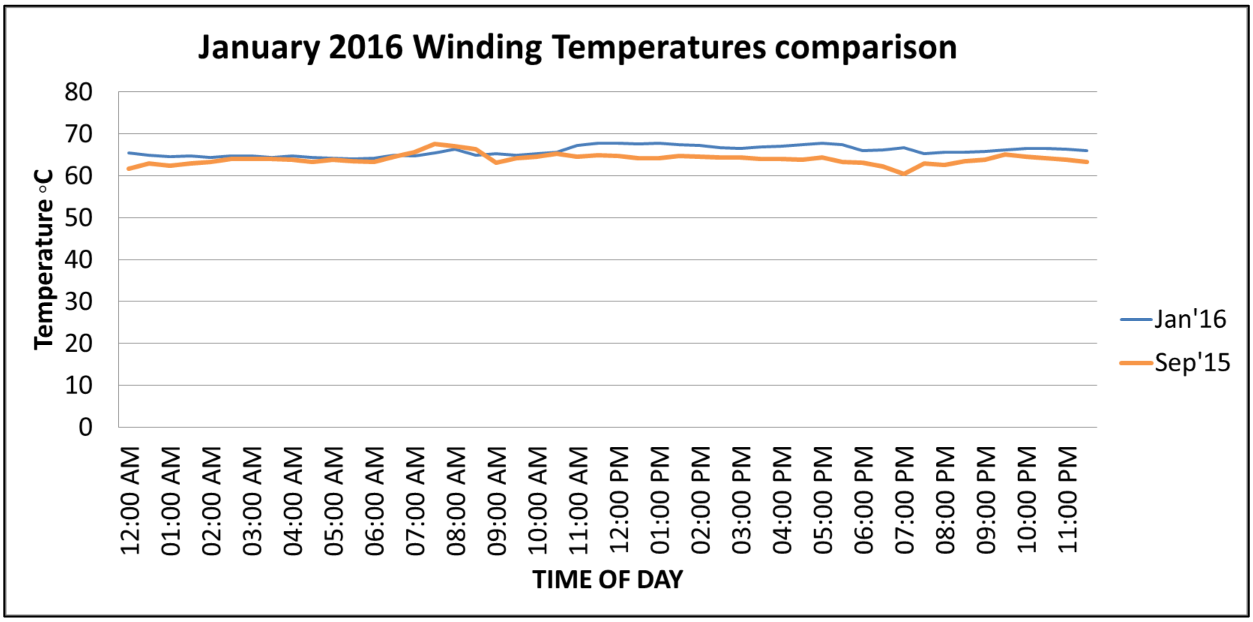


Figure 128 – Auto Solenoids Jan 2016 Winding Temperatures

February 2016:

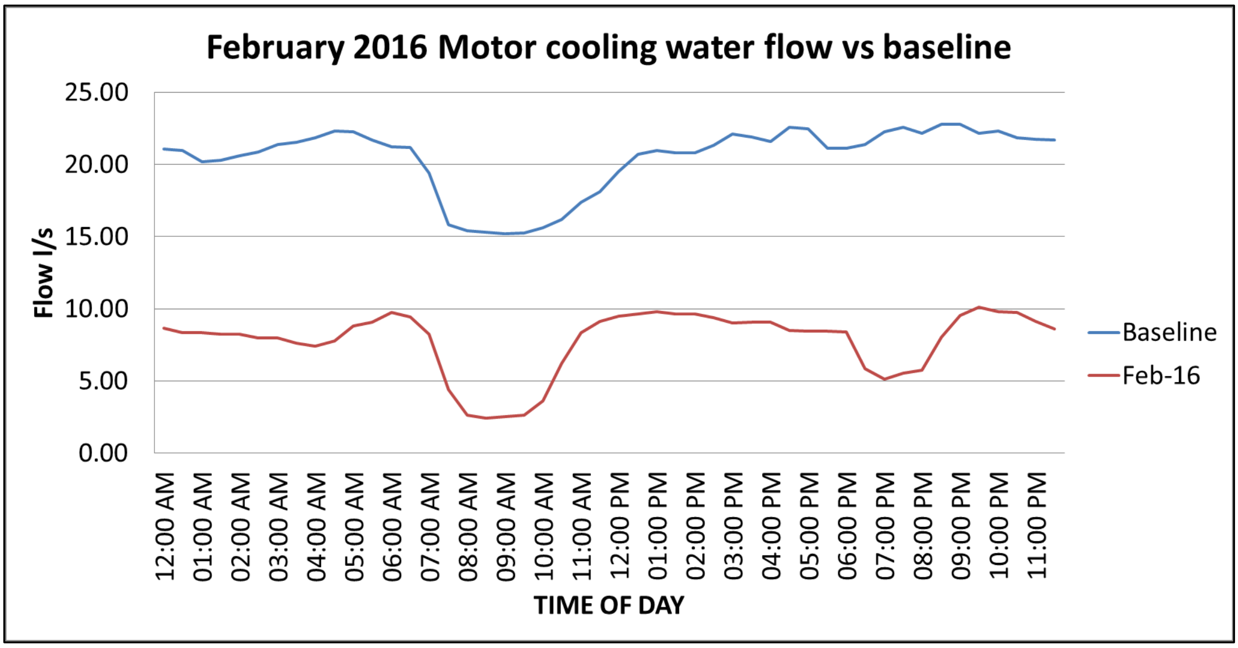


Figure 129 – Auto Solenoids Feb 2016 Performance

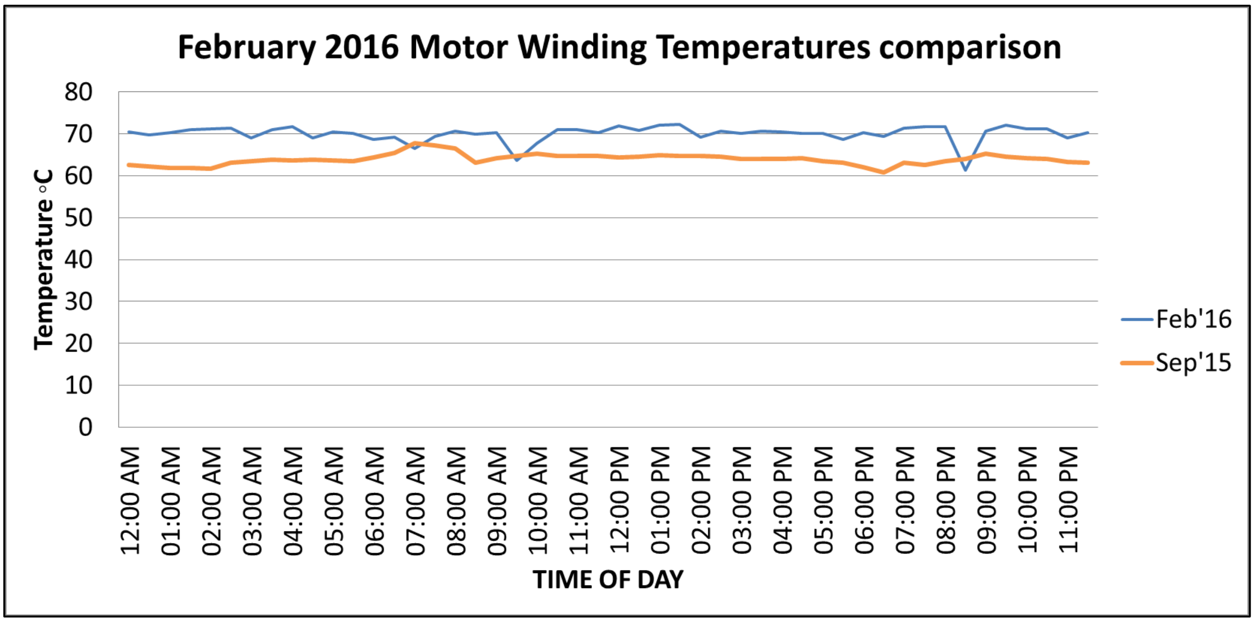


Figure 130 – Auto Solenoids Feb 2016 Winding Temperatures

March 2016:

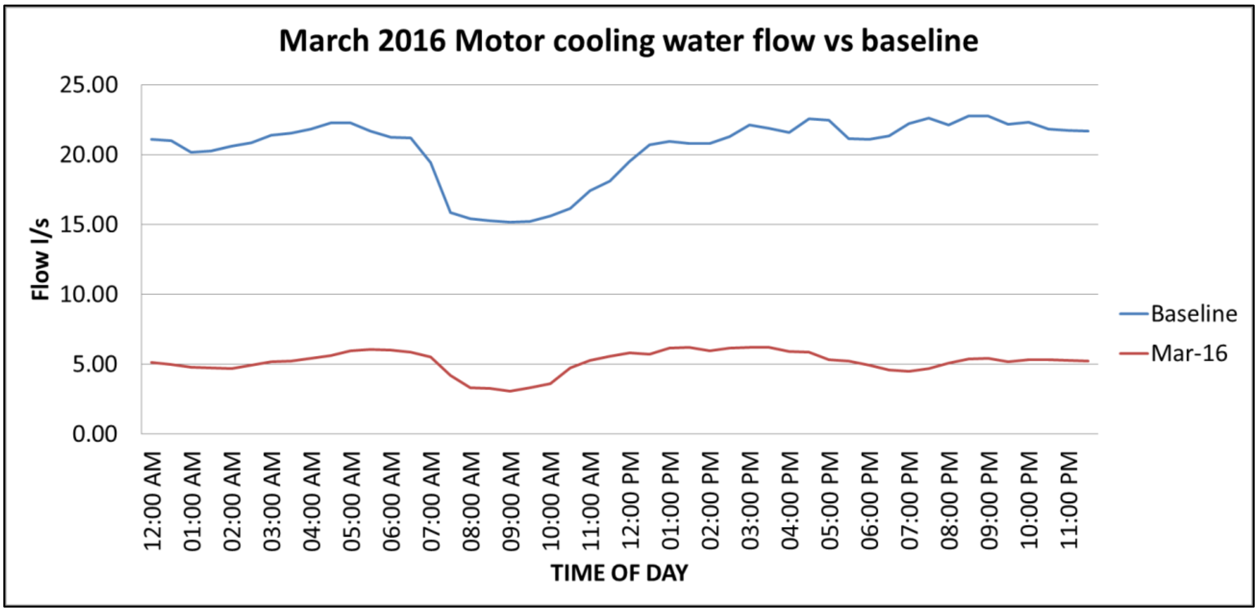


Figure 131 – Auto Solenoids Mar 2016 Performance

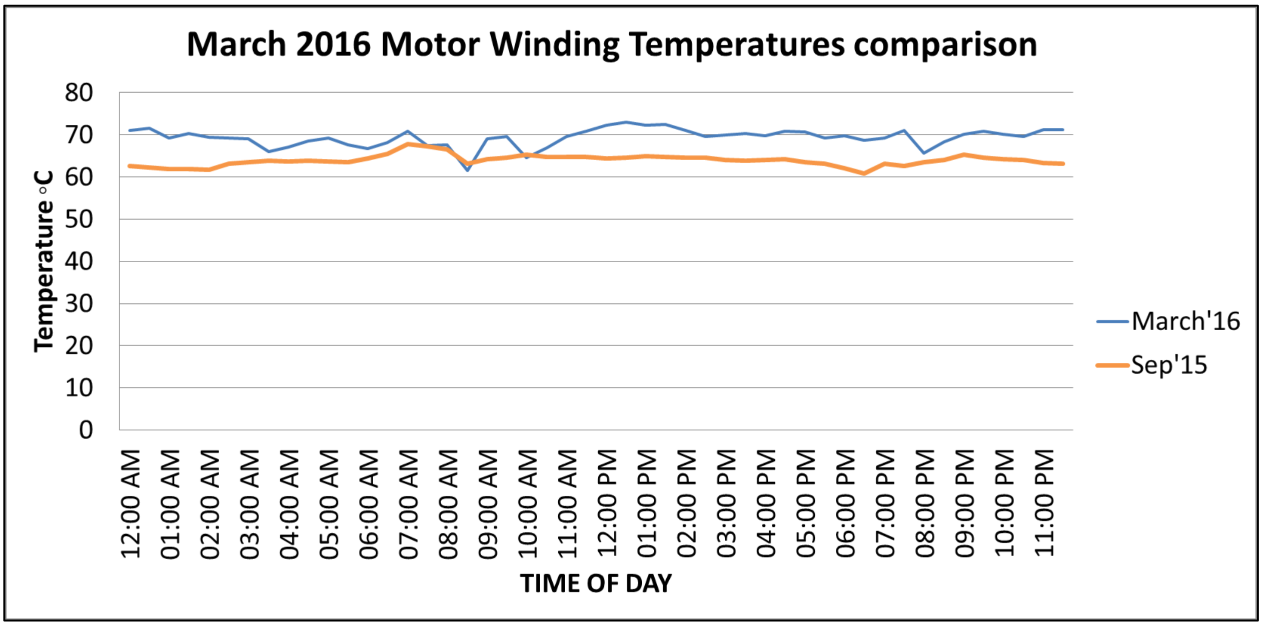


Figure 132 – Auto Solenoids Mar 2016 Winding Temperatures

April 2016:

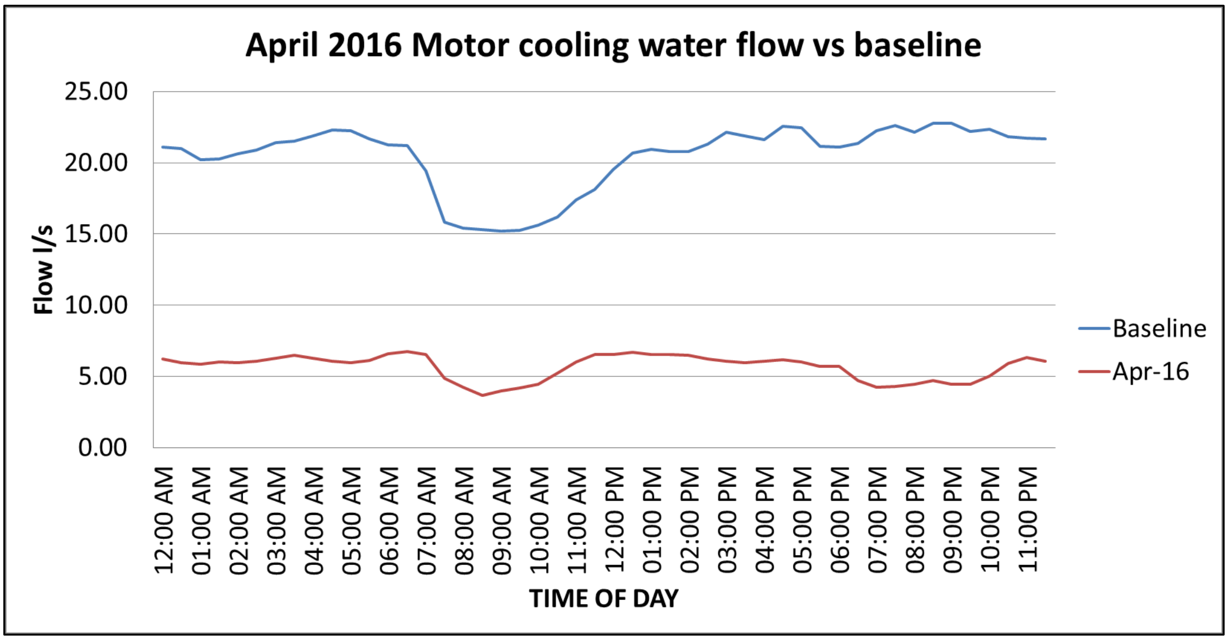


Figure 133 – Auto Solenoids Apr 2016 Performance

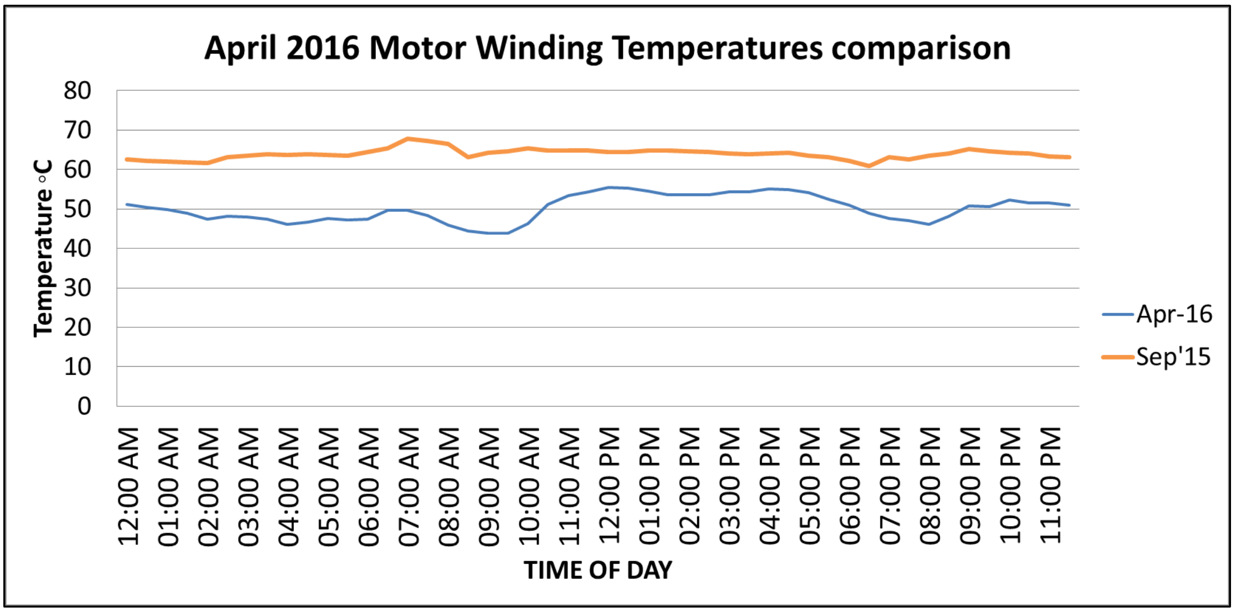


Figure 134 – Auto Solenoids Apr 2016 Winding Temperatures

May 2016:

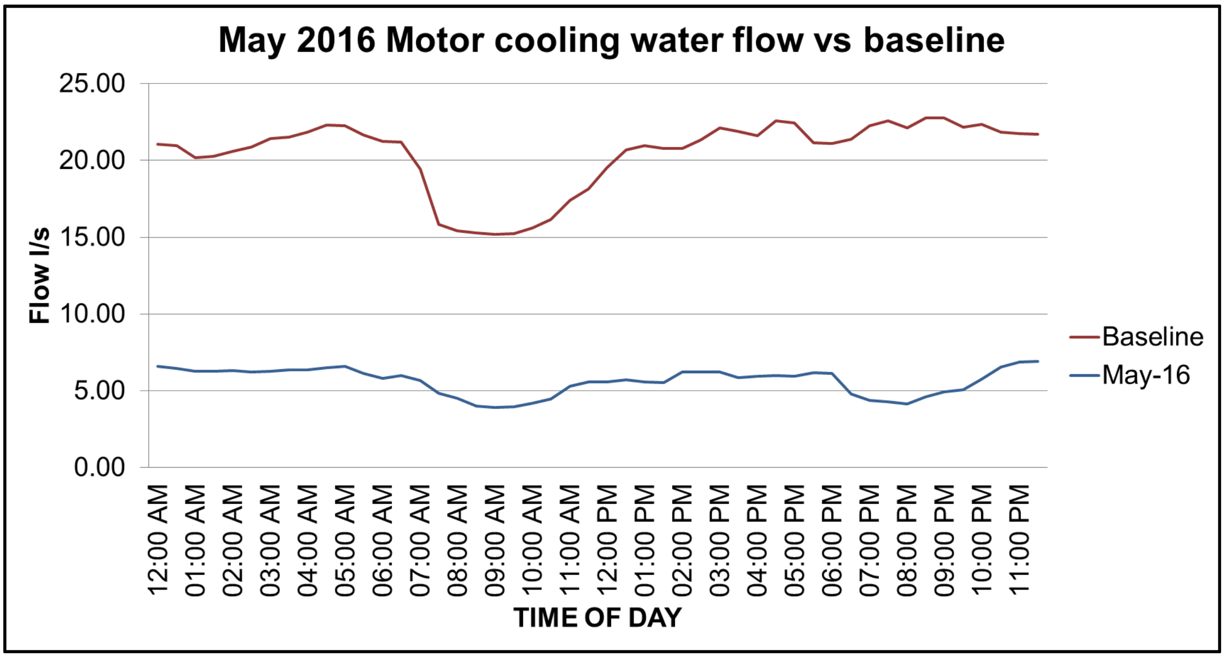


Figure 135 – Auto Solenoids May 2016 Performance

June 2016:

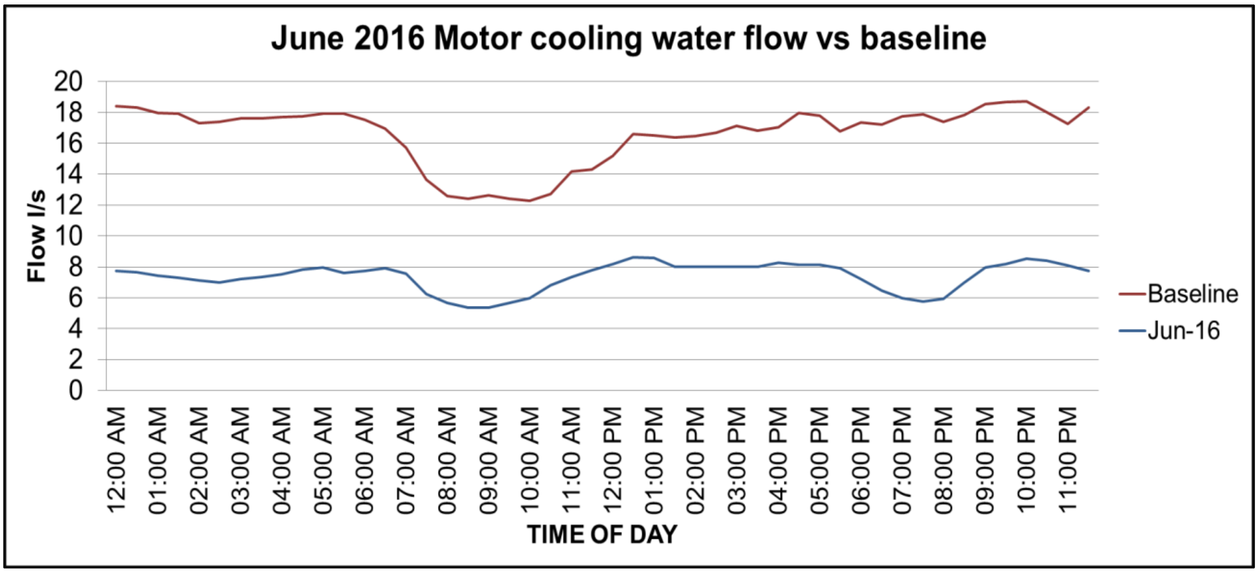


Figure 136 – Auto Solenoids Jun 2016 Performance

July 2016:

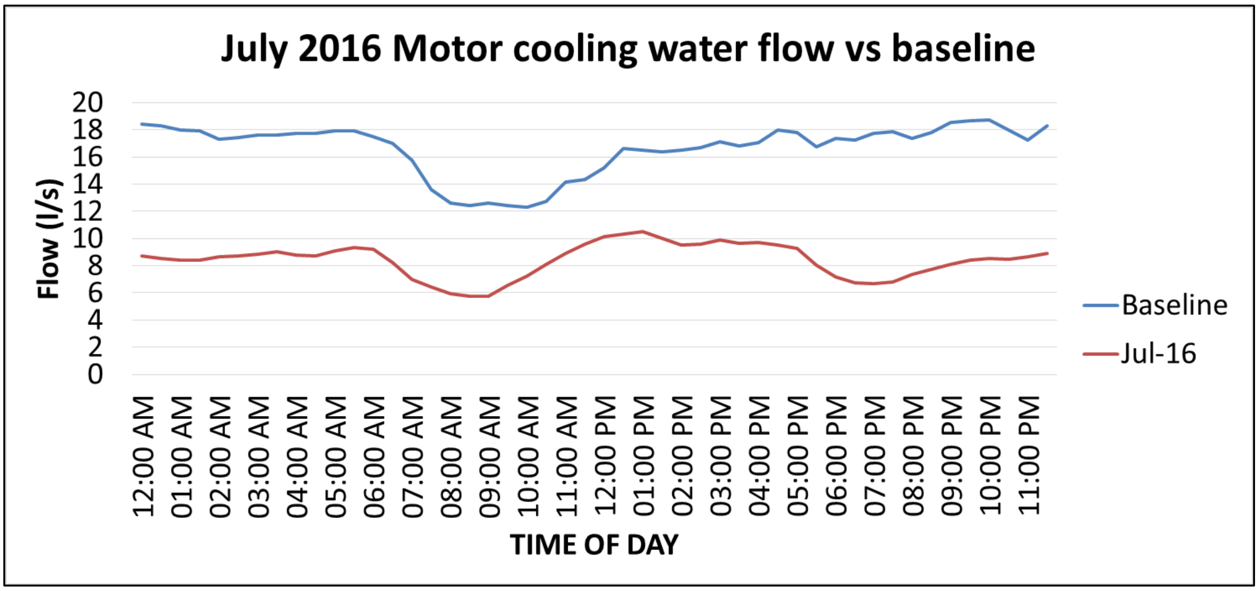


Figure 137 – Auto Solenoids Jul 2016 Performance

August 2016:

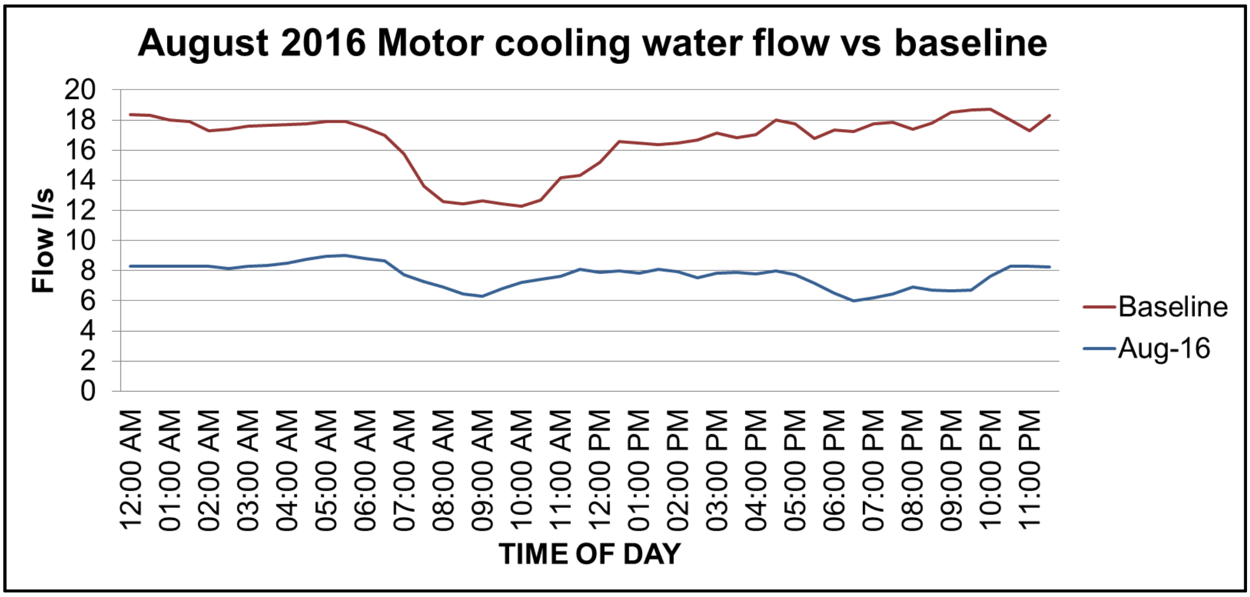


Figure 138 – Auto Solenoids Aug 2016 Performance