Performance and Cost Analysis of Utilizing Potable Water as a Hydronic Medium in Multi-unit Residential Buildings

by

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ABSTRACT

The use of potable water for hydronic purposes in buildings has been utilized for many years. Originally proposed as an energy- and cost-saving technique for single-family dwellings, it has evolved into systems that use potable water distribution to provide heating and cooling to multi-unit residential buildings of various sizes. Although the technique has been utilized for many years, the performance and efficiency, the effects of using potable water as a hydronic medium on water quality, and the long-term operational cost implications have yet to be explored through dedicated research. This has led to some skepticism of the technique, as well as claims regarding costs and performance which are not substantiated.

This research establishes a technique to evaluate the performance of the entire building system in a manner that can be easily communicated to the owners and operators of the building. This involves establishing the building efficiency as steady state efficiency and a standby loss, a methodology previously presented for individual appliances, but not explored for both the heating and cooling performances of complete building systems. The impact on the palatability of the water is established using trained panelists who are provided with blind samples of water from multiple sources in accordance with established human evaluation techniques. After the panelist data is compiled, it is confirmed that utilizing potable water as a hydronic medium has no noticeable impact on the occupant perceptions of the water when the water in the system is changed out on a daily basis through occupant consumption. Finally, the issue of long-term operating costs is explored utilizing a novel technique that utilizes object-based simulation. The difficulty with conventional life cycle analysis methods is that they utilize set values for weather, utility costs, and maintenance, all of which are dynamic attributes with differing volatilities. The object-based simulation includes the weather distribution for the location in question paired with the historical rates of change in utilities and labor to establish a cumulative distribution function of the direct comparison of long-term costs between two systems. This allows the evaluator to not only establish the probability that one system will have a lower life cycle cost over another system, but also the degree of savings.

PREFACE

This thesis is the original work of the author, Robert Prybysh. Three journal papers related to this thesis have been prepared for submission or published and are listed below. This thesis is organized in paper format following the paper-based thesis guidelines.

1. Prybysh, R., Fleck, B., Al-Hussein, M., Flemming, S. (2018). "Experimental study of the performance of residential buildings utilizing potable water as a hydronic medium", *Journal of Building Engineering,* 16, pp. 220-227.
2. Prybysh, R., Al-Hussein, M., Fleck, B., Sadrzadeh, M., Osolu, J. (2018). "Experimental study into palatability impacts of potable water as a hydronic medium", *Water,* 10, 218.
3. Prybysh, R., Gül, M., Fleck, B., Al-Hussein, M. "Object-based life cycle simulation as a decision tool for the selection of building mechanical systems", *Journal of Construction Engineering and Management* (For Review).

The research project, of which this thesis is a part, received research ethics approval from the University of Alberta Research Ethics Board, Project Name "Effect of System Residency Time on Palatability of Potable Water in HVAC Systems", No. Pro00051021, August 26, 2014.

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NOMENCLATURE

PLC	Programmable Logic Controller
ƍ	Delivered efficiency (%)
Ew	Thermal energy in the delivered service water (joules)
Eh	Thermal energy in the delivered heating airflow (joules)
Hg	Combustion energy of the natural gas (joules)
η	Steady-state delivered efficiency (%)
qin	Input rate (watts)
qout	Output rate (watts)
qloss	Idle loss rate (watts)
COP	Coefficient of Performance
E_c	Thermal energy in the delivered cooling airflow (joules)
He	Electrical energy consumed through system operation (joules)
COP_{ss}	Steady-state coefficient of performance
E_{capl}	Thermal energy extracted by the cooling appliance (joules)
H_{ep}	Electrical energy consumed by pumps (joules)
H_{ef}	Electrical energy consumed by fans (joules)
H_e	Electrical energy consumed through system operation (joules)
S_i	Sensitivity coefficient
dL	Change in output
L_n	Base value of output
dP_i	Change in input parameter
$P_{i,n}$	Base value of input parameter
Cr	Consumption ratio (days)
S_v	System volume (gal)
O_c	Occupant daily consumption gal/day)
HDD	Heating Degree Day
CDD	Cooling Degree Day
CAN$	Canadian Dollars
LCC	Life Cycle Cost ($)
BC	Building Cost ($)
MC	Maintenance Cost ($)

OC	Operating Costs (\$)
SC	Salvage Costs (\$)
n	Number of years of operational life (years)
MC_i	Maintenance costs in an individual year (\$)
OC_i	Operational costs in an individual year (\$)
MC_j	Maintenance cost in an individual month (\$)
OC_j	Operational cost in an individual month (\$)
HDD_j	Heating degree days in month j
CDD_j	Cooling degree days in month j
Hg_{HDD}	Quantity of natural gas consumed per HDD (Gj)
$Hg_{\$}$	Cost of natural gas (\$/Gj)
He_{HDD}	Quantity of electricity consumed per HDD (kW)
$He_{\$}$	Cost of electricity (\$/kW)
Hg_{CDD}	Quantity of natural gas consumed per CDD
Hec_{DD}	Quantity of electricity consumed per CDD
$\frac{dHg_{\$}}{dt}$	Derivative in price of natural gas between months (%)
$Hg_{\$j-1}$	Price of natural gas in previous month (\$)
INF_j	Inflation rate for the specific month investigated (%)

CHAPTER 1: INTRODUCTION

1.1 Research Motivation

The ongoing pursuit of reduced energy use in buildings and reduced cost of construction has led to the development of numerous types of building systems and operational techniques, each with the promise of reducing costs for the constructors and building operators. One such system is the use of potable water as the hydronic medium for distributing energy in a building for HVAC purposes. Originally developed in response to increased energy awareness in the United States during the 1970s as a means of heating single-family dwellings, the original concept involved the use of a single drafting hot water tank to both generate service water and provide heating (Caron et al. 1983; Subherwal 1986). The practice of using a single thermal generator in a single-family dwelling has expanded significantly in recent years, substantially as a result of the development of service water generators with increased efficiencies due to the development of condensing technologies, and the ability to operate continuously (Glouchkow et al. 2004).

1.2 Objectives

This research is built upon the following hypothesis:

> *"The use of potable water as a hydronic medium in multi-unit residential buildings results in systems that are efficient, safe for the occupants, and cost effective to construct and operate."*

This research proposes an investigation into the performance and costs of systems which utilize potable water as a hydronic medium, and to establish operating criteria for designers to reference when working with these systems.

The objectives of the present research are three-fold, and involve the review of the performance of systems that use potable water as a hydronic medium, the evaluation of the impacts of such systems on the occupants, and the evaluation of the costs and financial benefits.

1) **Establish the performance of systems that use potable water as a hydronic medium.** During this stage, a multi-zoned heating system is constructed to scale and is operated under set conditions and operating set points in order to establish the performance throughout the range of operating points and evaluate the impact of occupant behaviors on the performance of these systems. In addition to evaluating the heating performance, an evaluation into the performance of utilizing potable water as a hydronic cooling medium is completed.
2) **Evaluate the impacts of utilizing potable water as a hydronic medium on the occupants of the building.** This research aims to address the concern that heating service water changes (*i*) the palatability of the water, and (*ii*) what is the perception of the building occupants. During this stage, an evaluation of the service water by means of a flavor profile analysis technique to determine if the perceptions of the occupants in terms of alteration of the flavor of the water by using the water as a hydronic medium is completed. Additionally, in cases where changes in the perception of the water exist, this research determines the extent of such changes as well as establishing criteria in order to minimize occupant impact.
3) **Evaluate costs and financial benefits of using potable water as a hydronic medium.** Using potable water as the hydronic medium results in a system that utilizes less piping materials than separated systems. In theory, this would result

in lower costs for installation and potentially operation. Through the completion of a cost analysis, not only on the installation costs of the system, but also as a comparison of the life cycle costs when compared to other systems, these costs can be compared. A true comparison of these systems requires a novel means of considering Life Cycle Cost Analysis as current techniques do not consider economic and climatic fluctuations that occur during the life cycle of a building system.

1.3 Organization of Thesis

There are eight chapters in this thesis. Chapter 1 identifies the motivation for the research, its objectives, and the organizational structure of the thesis. Chapters 3, 5, and 7 represent the published or publishable paper components of this thesis. The editing on these chapters was for suitability as part of a larger document with grammatical updates, but are materially as published or intended for submission. Chapters 2, 4, and 6 represent the literature review and methodology development that resulted in the published papers. Each chapter corresponds to a specific paper, with Chapter 2 corresponding to Chapter 3. These chapters endeavor not repeat the results presented in the published work.

Chapters 2 and 3 explore the efficiency and performance of systems that utilize potable water as a hydronic medium. The identification of the efficiency in a novel manner that allows the performance of a building to be characterized in terms of Steady State Efficiency and Standby Loss. These characteristics are properties of the building that remain constant under various

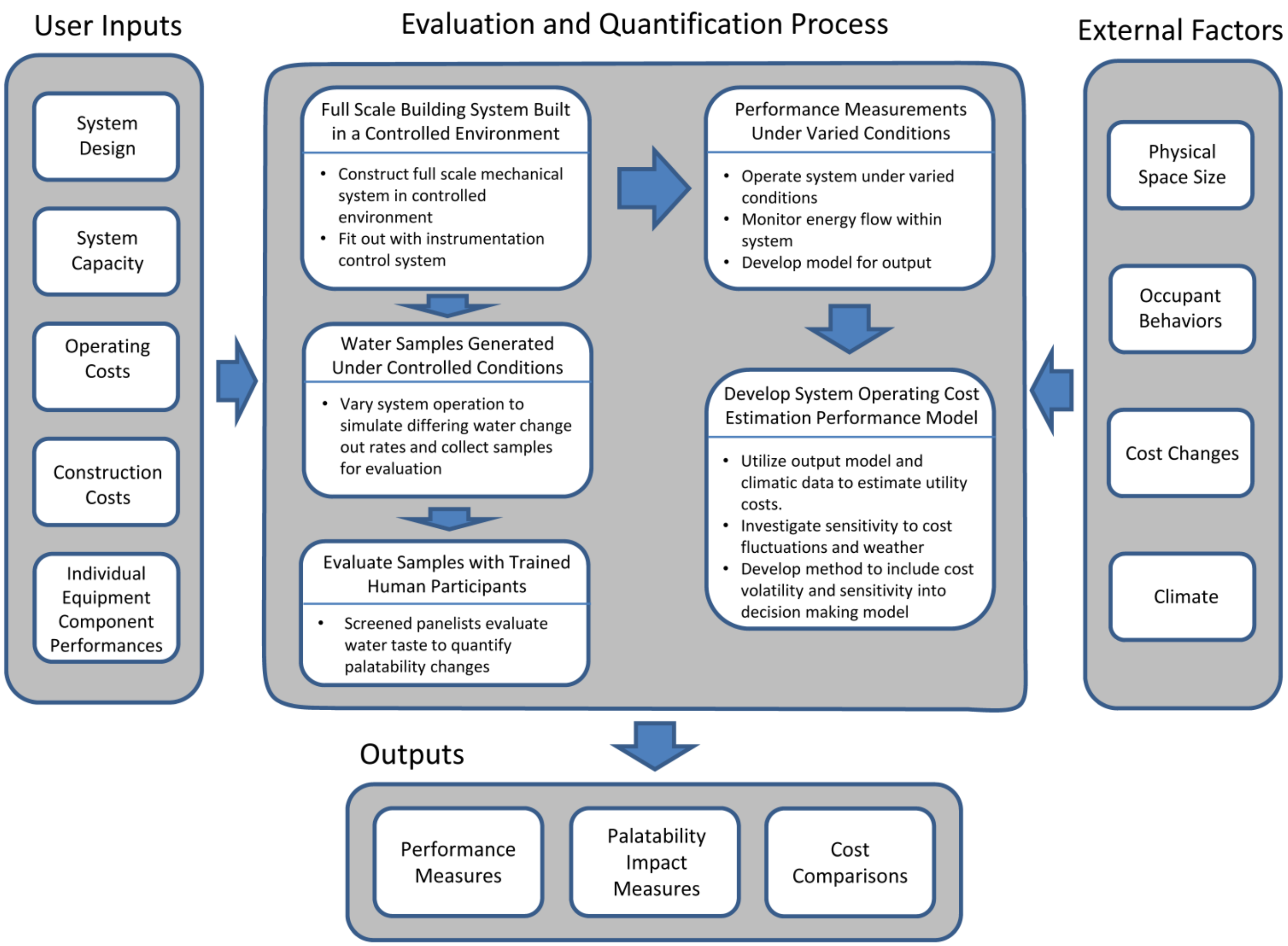

Figure 1.1: Process for the Evaluation of Potable Water as a Hydronic Medium

loading conditions, unlike conventional definitions of efficiency, which are subject to variation under part load conditions.

Chapter 4 and 5 present an investigation of occupant perceptions of the service water in a building delivered for use and consumption. To utilize potable water as a hydronic medium, it must remain potable. Continuously circulation exposes the water to repeated temperature cycles; and there is concern that the water could experience a chemical change that would reduce the perceived quality of the water by the occupants of the building. This chapter explores the relationship between system volume and occupant consumption in terms of the changes in occupant perceptions of the quality of the delivered service water.

One of the arguments presented in support of systems that utilize potable water as a hydronic medium is that cost-savings exist for both installation and operation when compared to other possible building systems. An investigation into these claims includes a life cycle cost analysis to evaluate if the long-term operating costs are actually less than comparable systems. During this investigation, it is determined that conventional life cycle analysis techniques may not provide a realistic result as they utilize static values for utility costs and environmental conditions, all of which are highly variable. By developing a simulation technique utilizing object-based simulation and data fitting, a Cumulative Distribution Function (CDF) of life cycle costs, or differences in life cycle costs between differing systems, could be produced. This provides both the probability of one system having a lower life cycle cost when compared to another, and also the information required to conduct a decision tree analysis. This simulation technique, explored in Chapter 6 and 7, produces a result that is more representative of realistic conditions, the outcome of which could lead the individuals responsible for selecting the building systems to make different decisions than they would base on the results from conventional life cycle analysis techniques.

Chapter 8 contains a summary of the conclusions, research contribution, and future work.

CHAPTER 2: LITERATURE REVIEW and EXPERIMENTAL DEVELOPMENT

2.1 History and Background

For decades, there has been consideration for the use of potable water as a hydronic medium. Hydronics is the process of using a liquid as a heat-transfer medium, and the use of potable water as a hydronic medium has specific characteristics. With interest peaking in the 1970's (Symposium on Use of Domestic Hot Water for Space Heating, 1971) as a means of providing low cost systems that were reliable for the occupants, research has since focused on the use of potable water systems in single-family dwellings (Butcher, 2007; Caron et al., 1983; Hayden ACS, 2012; Subherwal, 1986; Thomas M. , 2012). Even when use in multi-unit residential buildings is studied (Grant, 1971) it was referenced from a standpoint of installation costs, not system performance or efficiency. Review of prior research into the performance of systems that utilize potable water as a hydronic medium focused on two areas, reported efficiencies and reporting techniques.

2.1.1 Reported Efficiencies

The reported efficiencies of systems have fallen into a number of distinct categories, systems operated under a controlled environment and systems operated under actual operating conditions with occupant inputs. Studies that investigate the performance of multi-unit residential building at full scale have specifically excluded the effects of occupant behaviors (Zaheer-uddin, et al., 1989) as they can significantly alter the results (Sharmin, 2014). Due to the scales involved, the majority of studies appear focused on single-family dwellings and appliances that would service a single dwelling. Early studies into appliance and combined systems reported efficiencies in the range of 50% to 60% (Caron et al., 1983; Subherwal, 1986). While the appliances used in these studies specified higher efficiency ratings, and included high efficiency condensing equipment, they reported high standby losses that substantially reduced the performance of the systems when under partial loading.

It is important to note that this investigation is specifically reviewing efficiency as system input energy required to deliver system output energy, not input energy to achieve an intended outcome or condition. While altering a building envelope or other characteristic could affect the efficiency of a building, in terms of input/output energy required to achieve an intended outcome or condition, that is not the efficiency being investigated in this exercise.

Improvements into appliance performance led to improvements in system efficiencies that were observed when operating under controlled conditions (Butcher, 2007) leading to reported performances in the range of 70% to 80% for complete operating systems. Technology to limit standby losses led to further improvements (Thomas M. , 2012; Hoeschele et al., 2013; Der et al., 2017) and the use of instantaneous water heating technology resulted in system efficiencies in the range of 80% to 90%. Modelling the use of the systems to the statistical average use of water by simulated occupants resulted in the varied efficiencies reported for the higher efficiency studies. However, studies conducted using actual installations have shown that there can be a substantial effect on reported efficiency due to occupant behaviors (Schoenbauer et al., 2011). Additional modern study into combined systems has investigated the use of alternative energy sources such as solar, as the combined distribution with a single system services multiple functions (Dickinson et al., 2011).

2.1.2 Reporting Techniques

Reporting of efficiency of an appliance has shown to be difficult as the actual efficiency of an appliance is dependent on the loading of the appliance. When reducing the heat load, energy expended to maintain the standby losses becomes a larger portion of the energy inputted and the actual efficiency is reduced (Schoenbauer et al., 2011). As a result, proposing that implementing a linear model that utilized two parameters would be a better means of communicating the efficiency and would provide better information to operators (DeCicco, 1990). In the linear model, the input and output energy become the axis of the distribution. The steady state efficiency and the standby losses become the parameters that illustrate the characteristics of the system. Such a model is often used to illustrate the performance of appliances (Butcher, 2007; Hoeschele et al., 2013) and provides a clean means to communicate the efficiency of an appliance. As part of this study, there was an investigation into the performance of a complete full-scale system.

2.2 Development

To study the use of potable water as a hydronic medium to full scale requires a building operated in a controlled environment that can be monitored and manipulated to test the performance under differing controlled conditions. While a building can be a large object to construct to full scale in a controlled environment, this research only requires the heating/cooling systems and the service water systems. These systems make up a comparatively small portion of a building and are constructible to full scale in a controlled environment.

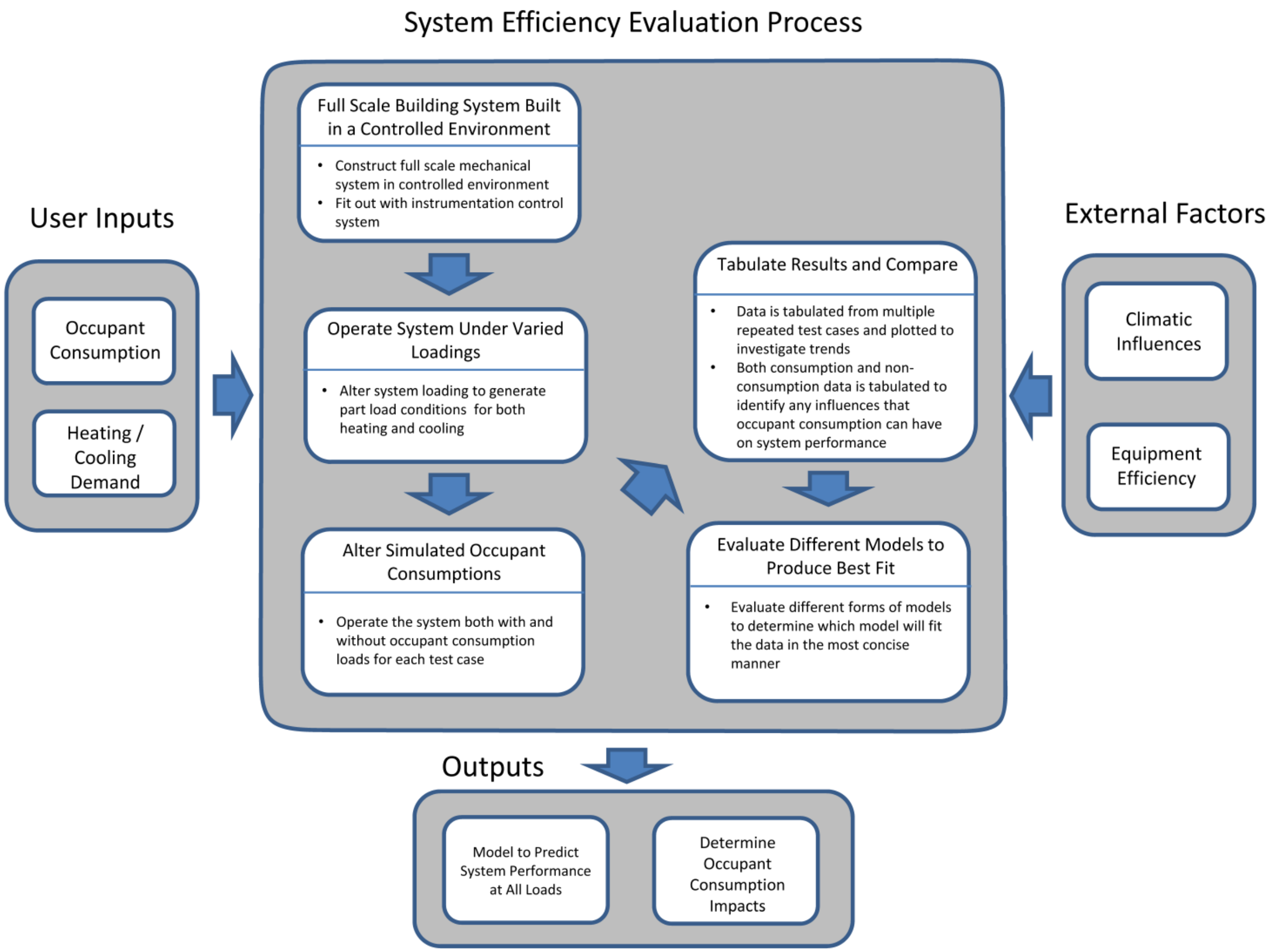

Figure 2.1: System Efficiency Evaluation Procedure

To reproduce a system in full scale, a configuration needs to be determined. The piping in a multi-unit residential building can have numerous configurations (Binggeli et al., 2016), but for this investigation, the system must incorporate a number of key considerations:

1. The intent of this investigation is to review systems that use a central plant to generate heating and cooling water.
2. The system must utilize the water as the service water for the building.
3. A terminal unit installed in each suite will be responsible for providing heating and cooling to the suite.
4. The system will investigate a four-pipe configuration.
5. The utilized laboratory space has height limitations.
6. Samples of designs available are low rise building (four to six stories) and have a piping distribution with a riser configuration.

Based on these considerations, the experimental apparatus was designed as a four-pipe fan coil system, constructed in a riser configuration with a single heating appliance and a single cooling appliance. Materials for the piping are limited to compounds that rated for use with potable water at the temperatures considered. Due to the low chemical leaching, the cold-water distribution used PVC pipes, and the hot water distribution used CPVC (Heim, 2006). A schematic for the proposed apparatus is included in Figure 2.1.

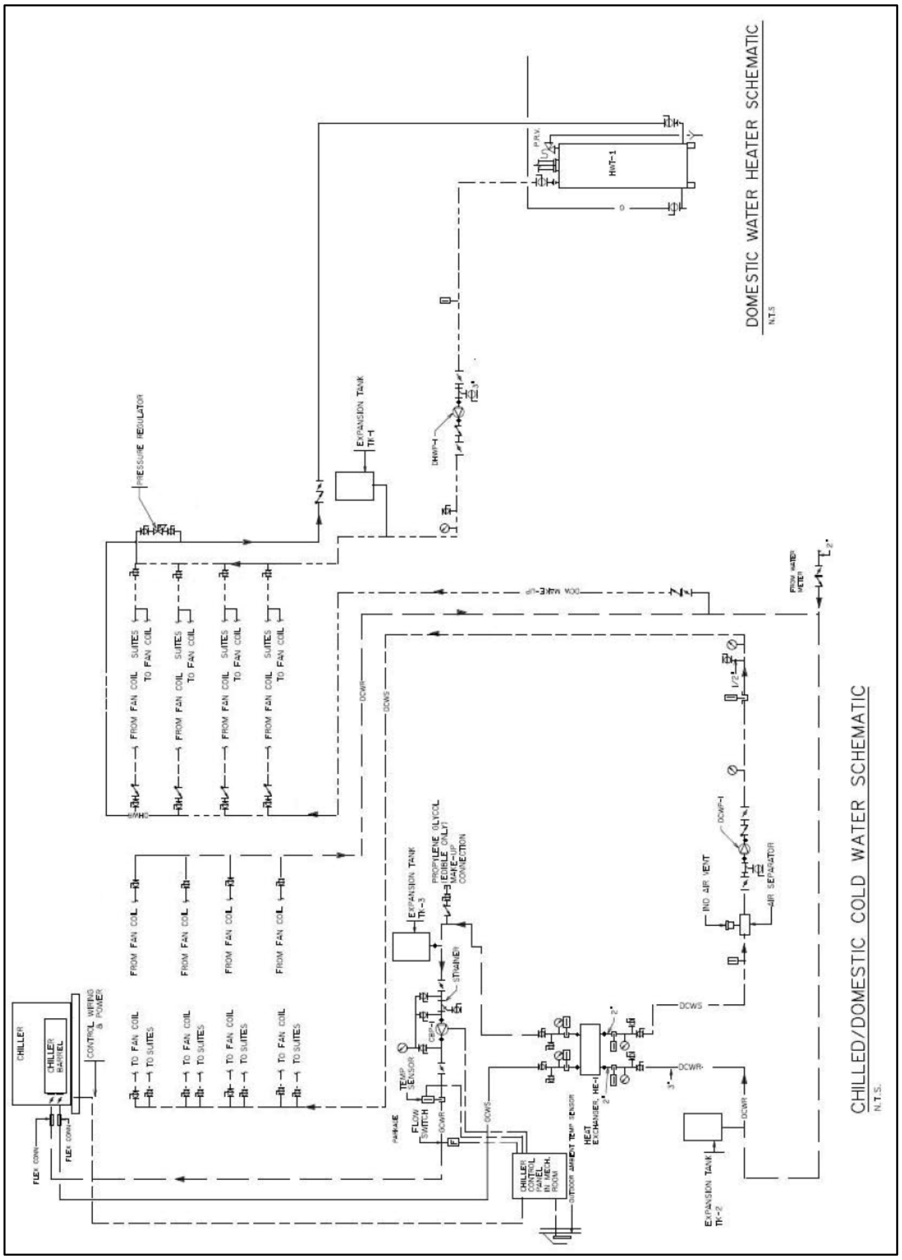

Figure 2.2: Schematic for the proposed apparatus.

A heat load conducted on a suite from a previously designed project derived the thermal load required to serve the simulated suites. Each suite was modelled to have a heating load of ~15,000 BTU/hr (4.4 kW) and a cooling load of ~8,000 BTU/hr (2.35 kW). Six simulated occupants resided in the four suites; this was adjustable during the study. Average daily water use was set to 75 gal/day (300 l/day), or which 2/3 would be hot water use (Alberta Safety Codes Council, 2012; Thomas et al., 2011; Chmielewska et al., 2017). From this design specification, equipment was selected and utilized to construct the apparatus. Documented details of the utilized equipment are in Appendix A for reference.

The addition of instrumentation to monitor the rates of energy usage and delivery occurred once the system was constructed and commissioned. The monitored items to establish the amount of energy entering and leaving the system was:

- Inlet temperature to each fan coil
- Discharge temperature from each fan coil
- Inlet relative humidity
- Discharge relative humidity
- Water temperature being discharged from the system
- Water temperature into the system
- Power consumed by each electricity consuming item
- Natural gas flow rate into the system
- Flow rate of cold source water entering the overall system
- Flow rate of cold water entering the hot water portion of the system

Additional measurements taken concerned pumped flow rates and water temperature at various locations in the system, but these were for commissioning and troubleshooting. Each of the fan coils was fitted with a discharge air damper to set a constant differential pressure across the fan coil of 0.15” Water Column (38 Pa). A pitot traverse in accordance with the Log-Tchebycheff rule for rectangular ducts measured the flow rate of air across the fan coils (ASHRAE, 2017).

Monitoring of electricity used a set of Brultech ECM-1240. This instrumentation provided an accurate measurement of electrical consumption in the form of consumed watts successfully on prior projects (Sharmin, 2014). Commercial flow meters approved by Measurement Canada for commercial use measured gas and water consumption.

With the system instrumented, a Programmable Logic Controller both recorded data and controlled simulated occupant activities. Apartment style residences are documented to have a relatively low variation in water consumption based on time of day (ASHRAE, 2015), as a result the occupants were simulated by utilizing hourly batch consumption. The collection of data occurred every 15 seconds, with each scenario operated for no less than 12 hours. Due to the long periods of data collection, the PLC was also fitted with a heartbeat to confirm operation. In the event of a computer failure, PLC failure, or water leak the system would isolate the water supply to the apparatus.

2.3 Analysis of Results

Initial investigation into the efficiency of the operating system resulted in an efficiency curve that had the characteristic elbow shape when measured across part load conditions when excluding occupant consumption from the scenarios. Programming consumption into the scenario produced a more stable plot, which still improved efficiency as the heating load was increased. Depicted in Figure 2.2 are the outputs with measurement error. Similar curves have been noted on individual appliance performances, both in service water only scenarios and scenarios where the appliance is providing both service water and space heating, although on separate distributions (Butcher, 2007; Chmielewska et al., 2017; Hayden ACS, 2012). It was proposed that the data would be better presented as a linear model which resulted in a better output that was more informative for the analyst (DeCicco, 1990; Bohac et al., 2010).

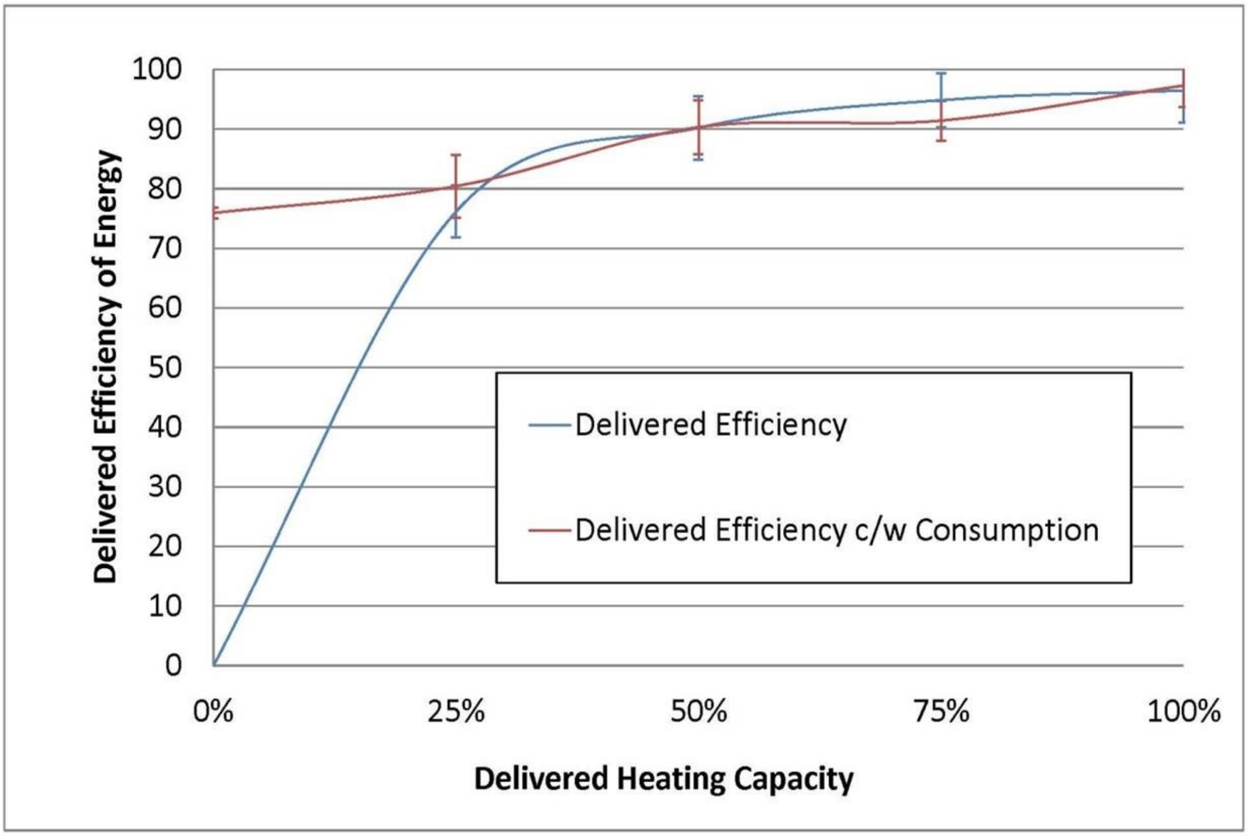

Figure 2.3: Initial Efficiency Results, including both consumption and non-consumption scenarios.

Published in Chapter 3 are the linear results from the operation of the apparatus through the range of tested scenarios. While the linear model did work well with the heating system, there was a lower correlation with the cooling scenarios. Further analysis as shown in Figure 2.3 identified that the linear model worked well when the cooling was operated as a closed loop system and occupant consumption was not included in the scenario. From the data plotted in Figure 2.4, the scenarios including consumption, it is clear that the consumption significantly influences the performance of the system, reducing the steady state Coefficient of Performance, increasing the standby loss, and increasing the variability of the measured results.

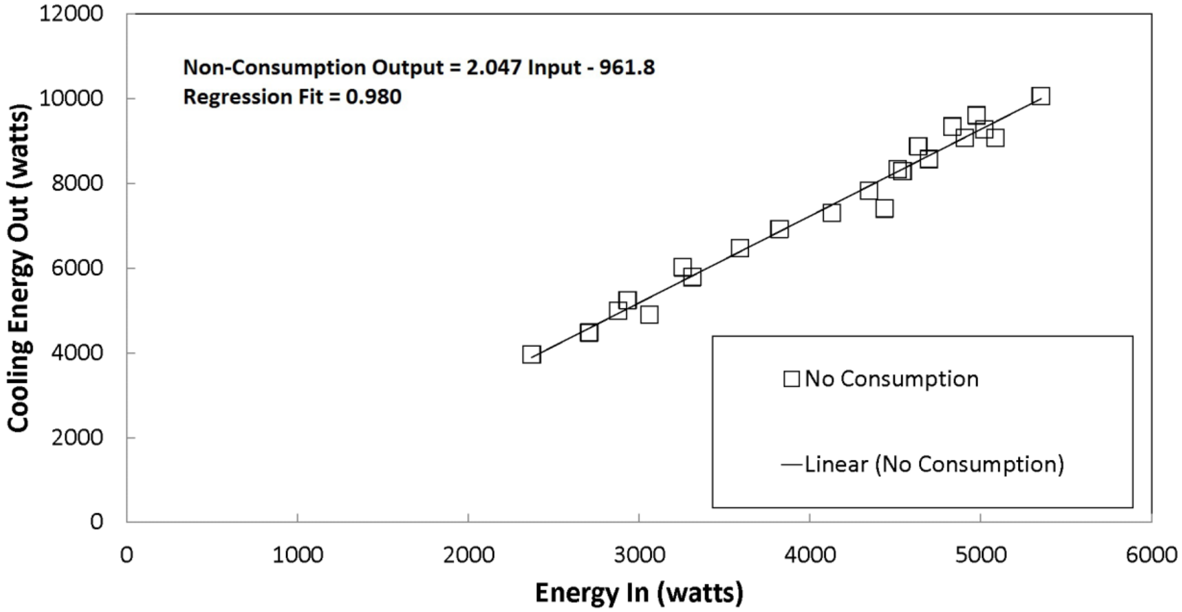

Figure 2.4: Cooling results with no occupant consumption fit well to a linear model.

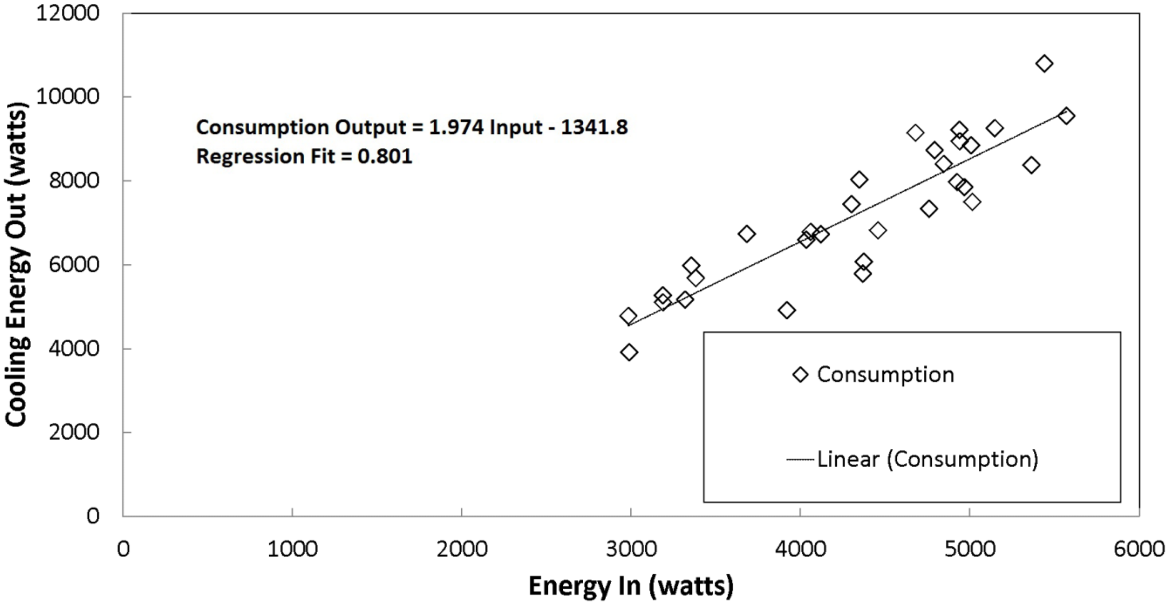

Figure 2.5: Cooling results with 75gal/(day*person) occupant consumption added to the scenarios resulted in reduced COP and increased variability of results.

As the only impact between the two sets of scenarios is the inclusion of occupant consumption, it is clear that this is the cause of the variations, although there is uncertainty in the means that derived this effect. As presented in Chapter 3, the hypothesis is that it is a result of variability in delivered cold service water temperature. There should be future analysis to investigate the effects of inlet water temperature on performance.

CHAPTER 3: EXPERIMENTAL STUDY of the PERFORMANCE of RESIDENTIAL BUILDINGS UTILIZING POTABLE WATER as a HYDRONIC MEDIUM[1]

3.1 Introduction

The use of potable water as a hydronic medium has been a concept of interest for many years, originating as a technique for heating single-family homes (Caron et al., 1983; Subherwal, 1986; Butcher, 2008). Numerous patents have explored this technique with the intent of reducing the amount of installed infrastructure necessary to satisfy the needs of building occupants, often looking for ways to use single piping systems for multiple purposes (Clark, 1993; Janus, 2001). While these systems have been proposed and are increasing in popularity (Springer et al., 2012), there are still many concerns in the industry regarding the implementation of such systems (MacNevin, 2016; Canadian Institute of Plumbing and Heating, 2008) and there has not been an in-depth published review either of the effects of utilizing potable water as a hydronic medium in a multi-unit residential building nor has there been an assessment of the impact of occupant behavior on system performance. Furthermore, the lack of recent empirical data on buildings that use these systems makes it difficult for designers to communicate the expected performance of the building as a whole (Arena et al., 2013).

3.1.1 Background on Potable Water as a Hydronic Medium

It is important to identify the differences in energy flows of a system that utilizes potable water as a hydronic medium compared to separately piped systems. In a traditional system, there are

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[1] The manuscript appearing as Chapter 3 of this thesis was published in the January 2018 edition of the *Journal of Building Engineering (Elsevier)* at the time of publication of this thesis.

separate hydronic heating water and the service water distributions. The building heating system can vary, due to the wide range of closed distributions and terminal units, but as is depicted in Figure 3.1 the underlying concept is common to all traditional systems: the service water system is independent from the heating system, with isolated thermal inputs and distribution. Heating water temperature can vary, but is often be in the range of ~ 82 °C (180 °F). Lower temperatures used for high efficiency systems and district systems use higher temperature distributions. Service water will commonly be limited to a range of 48 °C (120 °F) to 60 °C (140 °F) for safe use by occupants.

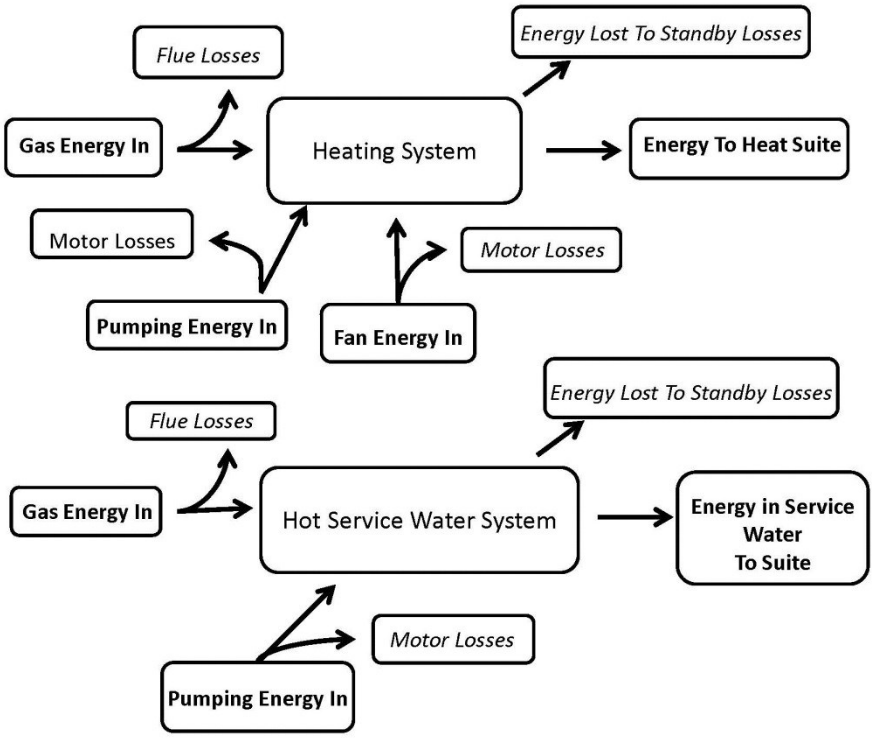


Figure 3.1: Energy flow profile for conventional separated systems.

Larger hydronic systems often implement a combined system, a system where the distributions are separate but as shown in Figure 3.2, sharing the thermal input between the heating system and the service water system. This type of system will feature an exchanger between the two distributions to prevent material intermixing since the fluids found in the respective distributions are not compatible. In the event that aggressive water treatment or freeze protection is included with the heating system, a double-wall exchanger may be required, thereby sacrificing thermal transfer ability to protect the safety and integrity of the potable service water. There are a number of benefits to sharing a thermal input between the two systems, such as the ability to reduce equipment size due to shared diversity, and increased overall thermal efficiency due to increased equipment utilization (ASHRAE, 2011). Alternatively, a system could use the hot service water system as the source, but this can limit the water temperature of the heating system to ranges that comply with local codes and guidelines, which are typically lower than 71 °C (160 °F).

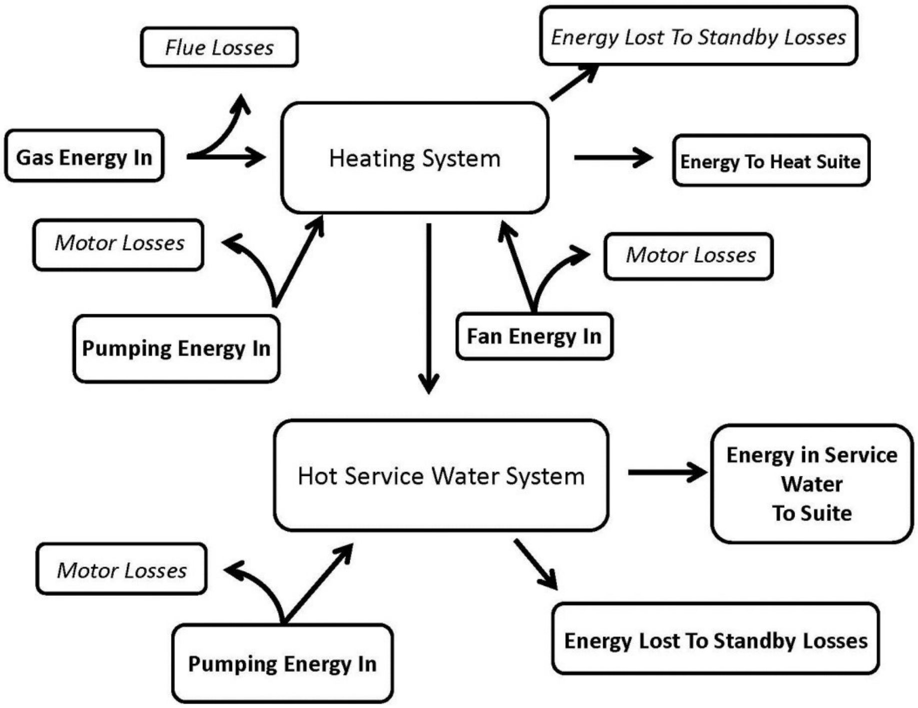


Figure 3.2: Energy profile for a conventional combination system using single thermal generator as the energy source for both heating and service water.

Using potable water as a hydronic medium takes the concept of system integration one step further; not only the thermal generation, but, as is shown in Figure 3.3, the entire distribution system is shared. In theory, this not only capitalizes on the benefits of a separated combination system, where the duty cycles of a constant operating and intermittent operating system are combined for the thermal generating equipment, but also applies these benefits to the piping distribution and circulating equipment. The hydronic heating water functions as the facility's hot service water, so operating temperature is limited to ranges compliant with local codes and guidelines. In light of this, it is necessary to design potable water heating distributions that use water temperatures lower than the conventional ~82 °C (180 °F) often used in closed loop heating distributions. Utilizing a delivered temperature under 71 °C (160 °F) provides the opportunity to implement heating equipment with efficiency performances that are associated with condensing appliances, especially when heating water temperatures are designed to operate in the range of 48 °C (120 °F) to 60 °C (140 °F).

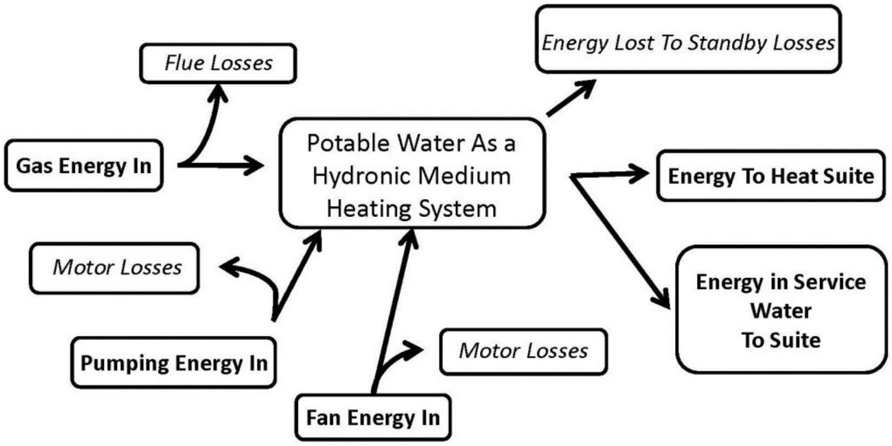


Figure 3.3: Energy Profile for a completely shared system utilizing the hot service water as the heating medium.

The prospect of utilizing potable water as a cooling hydronic medium has received less attention when compared to heating systems. The focus of studies into the use of potable water as a hydronic medium has typically been on single-family dwellings without hydronic cooling, but hydronic cooling is common in multi-unit residential buildings. Cold potable water has a more limited temperature range than traditional chilled water loops as many potable fixtures have components which are not insulated, leading to condensation concerns. This leads to the adoption of lower differential temperatures in order to avoid condensation on the fixtures, necessitating larger flows to meet the thermal demands of the service areas. This leads to a potential need for greater pumping energy, and therefore, potential negative effects on the system efficiency. Furthermore, there is an impact due to the inlet supply temperature of the service water to the system. As shown in the energy flow profile in Figure 3.4, the energy transfer from cold service water entering the system is bi-directional, dependent on the temperature of the water supplied by the utility to the building. The delivered temperature of supplied service water can vary depending on the physical region where the system is located, and this can affect the overall performance when utilizing potable water as a hydronic cooling medium. If the delivered service water temperature is less than the desired temperature for circulated cooling water, then there is the potential that the occupant consumption of potable cold water will improve the efficiency of the cooling system. Additionally, through its use as a hydronic cooling medium there is heating of cold inlet water with a low supply temperature. In theory, the system could use the preheated water as the source for the hot service water system. This would result in a reduction in the energy required to heat the hot service water used by the occupants, thereby improving the efficiency of generating hot service water. Unfortunately, it has not been determine if the improved efficiently would be impactful on the overall performance of the building system. Theoretically, the reverse is also potentially true, as mechanically cooling of warmer temperature delivered service water can result in lower system efficiencies.

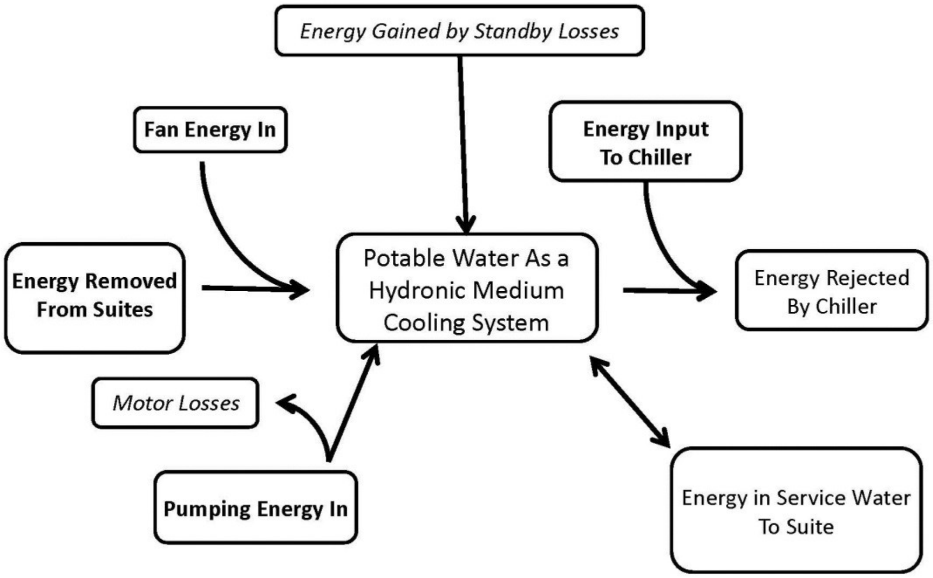


Figure 3.4: Energy flow profile using cold service water as the hydronic cooling medium.

3.1.2 Objectives

The key objective of this study is to establish a means to evaluate the efficiency of using a fully potable distribution for HVAC purposes, and to determine the parameters within which it is energy-effective to utilize a potable distribution versus a conventional separated distribution for both heating and cooling. In theory, the use of a potable water distribution should have no negative effect on the overall delivered system efficiency when compared to a conventional segregated distribution, but there have been some concerns that geographical location can influence the performance of such a system (Springer et al., 2012). The present research will investigate whether inlet water temperature can have a material impact on the performance of the system with respect to heating and cooling, and will evaluate and quantify this impact in order to determine the suitability of potable distributions for HVAC purposes based on geographical location.

3.2 Methodology

3.2.1 Experimental Design

Studying a potable heating distribution in a building effectively requires a heating mechanical distribution system constructed in a controlled environment. An apartment building with a riser configuration that is capable of delivering heating, cooling, and potable water to each unit provided the basis for the completed system. The system utilized the riser configuration because it is representative of the construction of many residential buildings with a central heating plant. This is consistent with both low-rise construction, where each riser may serve the entire height of the building, and high-rise construction, where the building often has separate vertical sections with each section served by an independent riser configuration. Such systems plumb water from the central plant to each suite, delivering it to the unit's plumbing fixtures or circulating the water through a potable rated fan coil then returning it to the central plant for re-conditioning. As such, all components utilized in the construction of these systems and our apparatus must have a potable water rating and the piping configuration permits circulation every 24 hours in accordance with local codes (Canadian Standards Association, 2012). Note that this introduces the requirement to continuously circulate the central multi-unit residential building distribution, which is different from the high-efficiency designs deployed in single-family dwellings. In single-family dwellings, the hot water generator can be an instantaneous hot water heater which takes advantage of limited standby losses (Hayden et al., 2012), or a high-efficiency hot water tank which only circulates on heating demand. Multi-unit buildings that use a central system do not apply this technique, as the volume of piping acts as a storage body and the distance from the central plant to the fixtures requires the system to have continuous circulation. Ultimately, this requires care to ensure that all components used in these systems and our apparatus are rated for use with potable hot water and are certified for continuous flow and operation.

In this study, the constructed apparatus included a 4-suite riser based on a riser system representative of a riser in a low-rise apartment building. Each suite was modeled as a single suite with a peak heating load of 3.5 kW (12 MBH) and a peak cooling load of 2.2 kW (7.5 MBH). Suites can vary substantially, based on construction and climate, but these values are consistent with local conditions. The model included an average of 1.5 occupants in each suite, for six adult occupants served by the simulated system. Water consumption at 300 L/day (~75 gallons/day) per occupant was modeled, consistent with local municipal design standards. The expected inlet water design temperature was 4°C (40 °F). Inlet water temperature, although it was expected to vary, so it was monitored and 4°C (40 °F) was only a design condition for selecting equipment. The system maintained the hot service water at 60 °C (140 °F), while maintaining cold circulated service water at 4°C (40 °F). The selection of particular fan coils, chillers, heat exchangers, pumps, and hot water heaters based on these conditions satisfied the design criteria.

The benefit of using an apparatus built to full scale to simulate a building is the ability to monitor the system under controlled conditions and minimize the influence of uncontrollable variables. A dedicated PLC (Programmable Logic Controller) monitored and controlled the system, controlling the hot and cold-water consumption of the simulated occupants with a timed routine. The PLC controlled the fan coils and control valves for the individual simulated suites, programmed for each operational scenario, although internal controls installed on each fan coil permitted the operation of a cycling routine, circulating the water in the coils once per 24-hour period in accordance with local codes (Canadian Standards Association, 2012). Furthermore, the fan coils installed in the conditioned space kept the operating environment at steady conditions. The discharge temperature for the hot water was set to 40 °C (100 °F) using thermostatic mixing valves and monitored at the point of water use for each scenario.

The system monitored and compensated for two variables with the potential to influence the scenario were not directly controlled. On open area was required for the chiller, but the environmental temperature of which could not be controlled. Monitoring of the environmental temperature and coordination with the manufacture specified performance profiles for the equipment addressed this. This allowed for the correction of the measured electrical consumption of the chiller to a standard temperature for all the scenarios tested. The inlet temperature of the service water to the system was the second variable that was uncontrollable. As the impact of inlet water temperature is of interest to this study, monitoring allowed for the evaluation of the effects.

3.2.2 Delivered Heating Efficiency versus Steady-State Heating Efficiency

The delivered efficiency for heating (ʒ) is the total thermal energy delivered as a proportion of the total energy added into the system. Delivered energy exists in two forms: (1) the heating of the air delivered by the fan coils, which is the portion that contributes to building heating (Eh), and (2) the portion delivered as heated service water (Ew). The total energy added into the system also exists in multiple forms; (1) the energy is being consumed by the hot water tank to heat the water (where natural gas is the predominant thermal source (Hg)), and (2) electricity being consumed by various components for normal operation (He).

Using these properties, the definition of the expected delivered heating efficiency (ȝ) is:

$$\text{ȝ} = \frac{(\mathbf{E_w+E_h})}{\mathbf{H_g+H_e}} \qquad [3.1]$$

where:

ȝ = Delivered efficiency (%)

Ew = Thermal energy in the delivered service water (joules)

Eh = Thermal energy in the delivered heating airflow (joules)

Hg = Combustion energy of the natural gas (joules)

He = Electrical energy consumed through system operation (joules)

Utilizing this format does cause a number of issues when communicating the efficiency of the system in a concise manner. When operating under a partial load, the delivered efficiency (ȝ) described in Equation 3.1 becomes non-linear (Hoeschele, 2013), and given that a building will very rarely operate under design conditions, this limits the usefulness of this definition of efficiency when communicating the performance of the system to building owners and operators. Previous studies have proposed that, when reviewing the performance of an appliance, there is a linear relationship between the output energy and the input energy required to operate the system. (Butcher, 2011; Butcher et al., 2011; DeCicco, 1990). Butcher et al, for instance, found that combined appliances operate at steady-state efficiency (η) with a set idling loss (Butcher, 2011):

$$q_{out} = \eta\, q_{in} - q_{loss} \qquad [3.2]$$

where:

η = Steady-state delivered efficiency (%)

qin = Input rate (watts)

qout = Output rate (watts)

qloss = idle loss rate (watts)

While the intention of the linear model is to demonstrate the performance of individual appliances, there is a hypothesis about its application to complete building systems, with the complete system idle losses comprising both the appliance idle losses and the piping idle losses. Here appliance idle losses would refer to thermal losses of maintaining the service water, while piping idle losses would refer to both non-recoverable thermal losses in piping installed in areas that unserved by the system (Maivel et al., 2014) and pumping losses associated with continuous recirculation if such an installed system. Unlike systems installed in single-family dwellings, where the distribution is inside the zone served, the distribution for multi-unit dwellings is outside the suites, so thermal losses in such a case represent inefficiencies in the form of energy delivered to unintended spaces.

There is also a difference between the delivered efficiency (ʒ) and the steady-state efficiency. As mentioned previously, the delivered efficiency (ʒ) varies with system load and is non-linear with the operating state of the system. Steady-state efficiency (η) is a set property of the system as a whole and will not vary under differing loads unless the operating conditions of the system are substantially changed. When using potable water as a hydronic heating medium, the water temperature is kept at a steady set point, normally without implementing temperature setbacks or outdoor reset. Given that the intent of the present research is to review the performance of systems that use occupant consumed potable water as a hydronic medium in comparison to systems that do not, the focus will be the steady-state efficiency.

For the system investigated in this research, the energy contained in the delivered service water represents the increase in service water enthalpy. The temperature of service water entering the system is recorded at the source, and the temperature of water leaving the system as hot potable water is recorded when the simulated occupants of the system consume the water. The airflow through the fan coils is measured once the fan coils have been balanced to a set external static pressure, and the inlet and discharge temperatures are measured to determine the delivered thermal energy. The quantity of energy delivered to the system is measured directly using gas and electricity consumption meters. Using the stated performances of the equipment selected for the system produces an estimation of the efficiency prior to operation.

The pumps used in this system are wet rotor units that use the circulated fluid for cooling; therefore, delivering any inefficiency into the fluid as heat. The same applies to the fans in the fan coils: all energy delivered to the moving fluid will eventually be in the form of thermal energy in the fluid, represented as 100% delivered thermal efficiency. Given that the steady-state efficiency (η) is independent of the idle loss rate (qloss), the steady-state efficiency (η) can theoretically be expressed as:

$$\eta = \frac{(\mathbf{X\,H_g+H_{ef}+H_{ep}+H_{ea}})}{\mathbf{H_g+H_e}} \qquad [3.3]$$

where:

η = Steady-state efficiency (%)

X = Rated thermal efficiency of the generating appliance

Hep = Electrical energy consumed by pumps (joules)

Hef = Electrical energy consumed by fans (joules)

Hea = Electrical energy consumed by auxiliary equipment (joules)

Hg = Combustion energy of the natural gas (joules)

He = Electrical energy consumed through system operation (joules)

For this experimental study, the selected heating equipment has a peak gas consumption rate of 35 kW (120 MBH) with a condensing heat exchanger, and rating the hot water pump with an electrical consumption of 85 W. Each fan coil is supplied with a motor that consumes approximately 300 W. The hot water tank is rated to consume less than 5 Amps at 120 V, which corresponds to a consumption of no more than 600 W. Based on these ratings, the gas consumption can be expected to be the primary determinant of system efficiency. Discounting the insulation losses (which will be part of the idle losses and can be considered negligible (Maivel et al., 2014)) and factoring in expected efficiency for a condensing appliance (manufacture-rated to 90% for the appliance used), a delivered steady-state thermal efficiency of 90.5% is calculated using Equation 3.3.

3.2.3 Cooling Efficiency

The performance of the cooling system is also estimated based on the delivered thermal cooling energy, or the thermal energy extracted from the building by the system, as a ratio of the total energy added to the system. With cooling, the delivered thermal cooling energy can exceed considerably the required energy, so the efficiency is measured as the Coefficient of Performance (COP). The COP is defined as “the benefit of the cycle (amount of heat removed) divided by the required energy input to operate the cycle” (ASHRAE, 2013).

When cooling, the energy consumed by the pumps and fans is still eventually delivered as thermal energy into the transported fluid, which contradicts the system intent of extracting thermal energy from the conditioned space. Defining the theoretical cooling performance as:

$$\mathbf{COP} = \frac{\mathbf{E_c}}{\mathbf{H_e}} \qquad [3.4]$$

where:

COP = Coefficient of Performance

E_c = Thermal energy in the delivered cooling airflow (joules)

He = Electrical energy consumed through system operation (joules)

This can be integrated into the linear model using the COP as the steady state COP for the system

$$q_{out} = COP_{ss}\, q_{in} - \sigma \qquad [3.5]$$

where:

COPss = Steady-state coefficient of performance

q_{in} = Input rate (watts)

q_{out} = Output rate (watts)

σ = Idle loss rate (watts)

In theory, the cooling energy delivered to the conditioned space would be the cooling provided by the chilling appliance minus the transport energy of the delivery fluid. The total electrical energy consumed by the system would be the electricity consumed by the cooling appliance plus the transport energy of the delivered fluid. From this, expressing the steady-state COP as:

$$\mathbf{COP_{ss}} = \frac{(\mathbf{E_{capl}} - \mathbf{H_{ep}} - \mathbf{H_{ef}})}{\mathbf{H_e}} \qquad [3.6]$$

where:

COP_{ss} = Steady-state coefficient of performance

E_{capl} = Thermal energy extracted by the cooling appliance (joules)

H_{ep} = Electrical energy consumed by pumps (joules)

H_{ef} = Electrical energy consumed by fans (joules)

H_e = Electrical energy consumed through system operation (joules)

While the cooling unit selected for this application has a rated maximum consumption of 28.8 Amps at 230 V, which equates to approximately 6.62 kW, the actual consumption is dependent on the outdoor dry bulb conditions and the type of cooling fluid used. Since the chiller operates in an environment where the outdoor peak cooling dry bulb is 28 °C and the minimum outdoor design temperature is -34 °C (National Research Council Canada, 2006), the system features an estimated fluid concentration of 50% propylene glycol in order to prevent damage in winter, and an output of 2.8 tons (9.8 kW) of cooling while consuming 3.3 kW of electricity. The cooling pump is rated to consume 185 W, and the fan coils consume 300 W each. When these values are used in Equation 2.6 a steady state COP of 1.8 is calculated (9.8 kW cooling capacity of the chiller, 185 W for the pump, and 1.2 kW for the 4 fan coils with 4.68 kW consumed (3.3 kW for the chiller, 185 W for the pump and 1.2 kW for the 4 fan coils)). The key determinant of the efficiency of the system is the consumption of electricity by the chiller, but the fan consumption energy is also a major contributor, accounting for more than 25% of the total electricity consumed by the system.

3.2.4 Occupant Behavior

One of the difficulties with using real constructed systems to determine baseline performance is that the uses of the system influence both the performance and energy consumption. Past experiences reported by design engineers in the field show that the performance and energy consumption of a system can vary by ± 50% from simulations due to the influence of occupant behaviors (Menconi et al., 2014; Yousefi et al., 2017). This has been confirmed in numerous studies monitoring the performance of buildings on a per suite basis by the variation that occurs between suites (Sharmin et al., 2014; Yan, 2015; Liang et al., 2016). This constitutes a considerable challenge when attempting to develop or validate models in a laboratory for systems that exist outside the laboratory (Brady et al., 2017). To address this challenge, the constructed apparatus is controlled in a manner that simulates a set occupant behavior. Measured water consumption rates for various building types have been previously documented and can be used to develop usage profiles for simulated occupants (ASHRAE, 2011). An interesting observation that has been identified regarding occupant water use is that apartments have a relatively steady water consumption rate when observed on a 24-hour time scale compared to other types of occupancy. This implies that even a stable per hour consumption is reasonable for simulating occupant consumption rates. However, while occupant consumption rates may be relatively stable on a per hour basis, they are not stable on an instantaneous basis. To capture this phenomenon in the simulated system, water consumption is simulated in a batch process with a specified amount consumed in short durations each hour, rather than as a continuous process. While it can be argued that larger residential building will have an occupant consumption profile that could be described, essentially, as a continuous flow, the population size required to achieve this profile is much larger than that of many buildings. The effect of varying the batch rate, size, or even simulating occupant consumption profiles as a continuous rate will be considered as part of a future investigation.

Daily total water consumption can be determined from local utility reports and municipal bylaws. Local communities provide minimal consumption rates on a per capita basis for design and simulation purposes (EPCOR, 2013), and published studies can be consulted to identify daily water use (ASHRAE, 2011). Based on the extracted information, water consumption is initially estimated at 300 L/person per day in the simulated system, with the ability to adjust the consumption rates for the purpose of simulating differing fixture efficiencies. The consumption is also split into one-third cold water and two-thirds hot water at the point of use in accordance with measured consumption rates (ASHRAE, 2011).

3.3 Analysis

Using the fully constructed apparatus, the operating performance was monitored under a wide range of operating conditions, both with and without consumption of water by the simulated occupants. Increments of operation were limited to the installed equipment, with the constructed apparatus simulating four suites of residential occupancy. Occupant consumption was kept constant for all scenarios. To observe any possible effects, scenarios included heating only, cooling only, and situations where both heating and cooling were operating simultaneously. Once the system was in operation, the thermal losses were estimated through observations and the theoretical performance curves were estimated using Equation 3.2 and Equation 3.5.

3.3.1 Heating Performance

Upon review of the thermal energy delivered by the system as depicted in Figure 3.1, it is found that the use of potable water as a heating medium does not negatively impact the ability of the system to deliver thermal energy to the point of use. The experimental data closely fits the linear model proposed, and, with the consumption of hot service water included in the operation of the system, the effect of the fit of the model is found to be extremely small and well within any variations that could be attributed to the experimental uncertainty of the apparatus. From the linear model, the steady-state efficiency (η) of the system is 92.6 % with an idle loss (qloss) of ~775 watts (Figure 3.5). This is a slightly higher steady-state efficiency (η) than originally estimated, but can be attributed to an actual appliance efficiency that is slightly higher than the rating specified by the manufacturer. Completing a regression analysis of the fit provides an

R2>98%, for the scenarios tested. From these data, it can be seen that the linear model technique proposed by Butcher (Butcher 2001) for modeling single appliances is applicable to larger systems found in large multi-unit residential buildings. This is an important finding which supports further large scale system based modeling experiments of this kind.

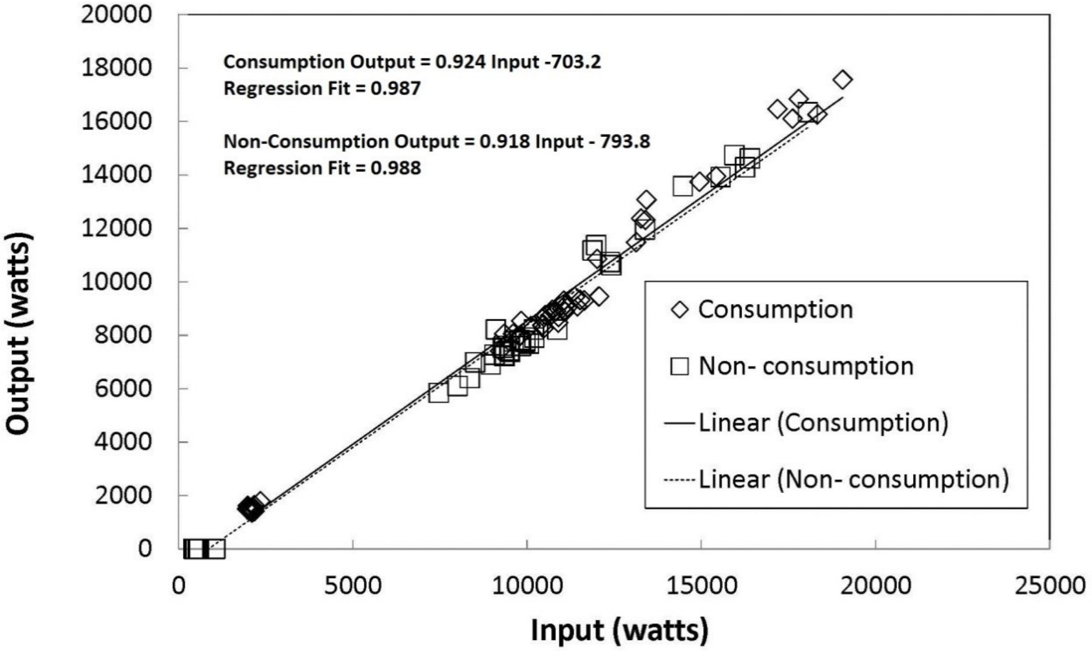


Figure 3.5: Recorded Heating Performance of the Laboratory System. The resulting whole building performances correlated well with linear modeling techniques intended for appliance only applications and the inclusion of occupant consumption did not measurable impact the performance of the system.

3.3.2 Cooling Performance

A review of the cooling performance data leads to a conclusion that differs from the one derived from the analysis of the heating data. While a review of the data yields a steady-state COP of ~1.8 for both the situations, where occupants consumed and did not consume the cold service water the idle losses are found to be approximately 50% higher when occupants consume the cold service water compared to when they do not (Figure 3.6). The correlation coefficient of the model also worsened substantially, from an R2=98% for the closed system to R2=80% for the consumption data.

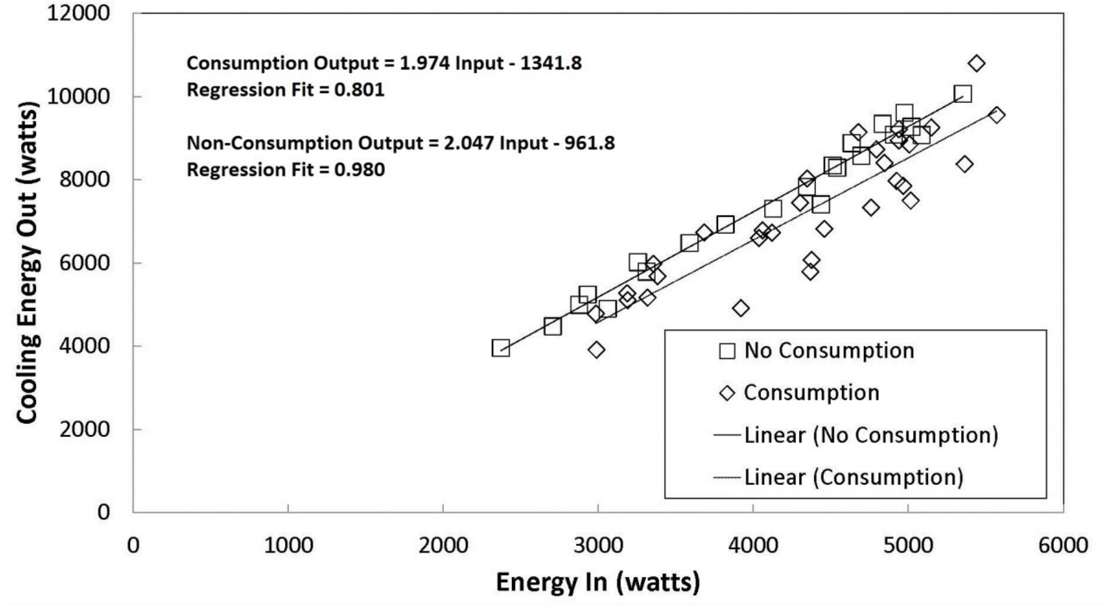


Figure 3.6: Recorded Cooling Performance of the Laboratory System. Fluctuations in the inlet water temperature resulted in a less cohesive distribution and increased inefficiencies when occupant consumption occurred.

The findings indicate that the inlet water temperature varied substantially and was often warmer than the target temperature targeted to provide cooling to the terminal units. As this would be a parameter that is not within the control of the operator of the system, it does pose as a hard limitation for the implementation of using potable water as a hydronic cooling medium in areas where the supply water temperature is be warmer than the target cooling water temperature. This is a limiting factor considering that the target water temperature used for hydronic cooling in this study was 4 °C (40 °F). Comparing this to a map of incoming potable water temperatures (Figure 3.7) derived from Collins (Collins, 1925) and specified by tankless water heater suppliers (Marey Tankless Water Heaters, 2015), it becomes clear that a majority of the North American market would experience additional idle losses when using a system that utilizes potable water as a hydronic cooling medium when compared to a closed system. Additionally, the temperature of the service water to the building can be coupled to the local surface air temperatures, which have been documented as increasing, resulting in increased temperatures of shallow water resources (Menberg, 2014). It also should be noted that the listed temperatures are a reported mean value and do not reflect the seasonal variations that occur in reality. Such variance can result in water distribution temperatures being much higher than reported (City of Medicine Hat, 2017) and this would have an impact on the performance of the cooling distribution. This also has an impact on the viability of utilizing potable water as a cooling medium. Increased shallow surface temperatures result in warmer service water, which this study has illustrated is associated with increased idling losses. While maintaining peak efficiency is feasible for certain parts of the continent as determined by the designed chilled water temperature, it would not be optimal to use potable water as a cooling medium except in northern climates.

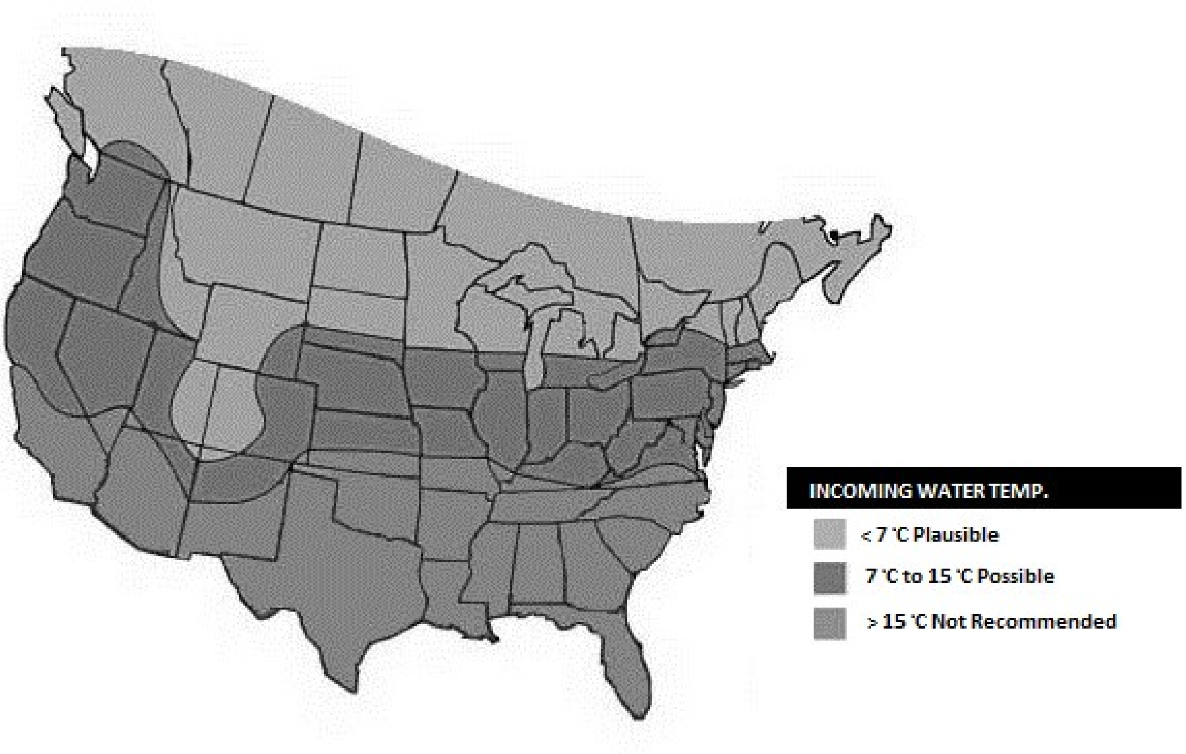


Figure 3.7: Average potable supply temperatures in North America with suitability recommendations for use with potable chilled water circulation. It can be observed that large portions of North America would not have suitable inlet water temperatures for the utilization of potable water as a cooling medium without incurring decreased efficiencies.

3.3.3 Parameter Influences

Evaluating the impact on the steady-state efficiency (η) of the performance of each component in the system is important as it allows for the identification of the major contributors to the efficiency of the system. In the present study this is carried out by conducting a physical parameter variation analysis using the generated data from the operation of the system (Silva et al., 2014; Saltelli et al., 2000) and evaluating a sensitivity coefficient for each parameter (Yu, 2013; Chow et al., 1995). In this case, the building itself is not the focus of the study, only the system itself and the parameters influencing the final outcome. These factors include, the combustion efficiency of gas-fired appliances, the electrical efficiency of electricity consuming appliances, occupant use of water, and the inlet water temperature. The sensitivity coefficient is evaluated as follows (Yu, 2013)

$$S_i = \frac{(dL/L_n)}{(dP_i/P_{i,n})} \qquad [3.7]$$

where:

S_i = Sensitivity coefficient

dL = Change in output

L_n = Base value of output

dP_i = Change in input parameter

$P_{i,n}$ = Base value of input parameter

Evaluating the steady-state heating efficiency (η) from Equation 3.3 for the data collected from a selected full load heating test scenario identities a Si of 0.92 for the appliance efficiency, 0.006 for electricity consumed by the fans, 0.0005 for electricity consumed by the pumps, and 0.004 for electricity consumed by the auxiliary equipment. These findings indicate that the efficiency of the heat-generating appliance is the main contributor to the efficiency of the overall system. The efficiency of the transportation equipment had a minor influence on the overall efficiency of the building system as a whole.

Conducting a similar evaluation of the steady-state COP from Equation 3.6 for the data collected for a selected full load cooling test scenario is more difficult as the consumption of power by the distribution equipment affects the energy available for cooling the suites. As a result, the thermal energy being addressed by the cooling appliance is considered a constant and the cooling energy delivered by the fan coils varies dependent on the transportation energy. This technique identifies an Si of 0.75 for the power consumption of the chiller, 0.36 for the power consumption of the fan motors in the fan coils in the suites, and 0.05 for the power consumption of the pumps. This is a significant finding as it indicates that the performance of the system is not only sensitive to the performance of the chilling appliance, but that the power consumption of the fan motors in the fan coils is also a substantial contributor. This is important to acknowledge, as small motors in fan coils are less efficient than larger motors (United States Department of Energy, 2010) and the efficiency is reduced considerably when the motor is not operating under full load (Rahman, 2012). Fan coils utilized in multi-unit residential buildings are typically mass-produced and are selected based on a worst-case potential performance requirement, not the actual expected conditions. As a result, there is significant potential for improvement to the building cooling performance through careful fan coil selection.

3.3.4 Deterministic Analysis

While it has been shown that the performance of the system is sensitive to the performance of various components used in the design and construction of the system, there are also elements which can have an impact on the performance of the system during operation. The collected data shows that when potable water is used as a heating medium, occupant water use or inlet water conditions have only a minor impact on the performance of the system. In contrast, when potable water is used as a cooling medium, it is apparent that varying inlet water conditions and occupant consumption can have a significant impact on the standby losses incurred by the cooling system. During this study, occupant water consumption increased the standby losses of the linear model by an average of 40% when occupant consumption was controlled. Individual tests showed a wide variation in standby loss increase, a phenomenon which led to the decreased regression fitness of the linear model to the data. Given that the occupant water consumption was set to a specific flow rate for the experiment, the variation in inlet conditions is the only remaining variable to explain the increase in standby losses. If occupant consumption had not been controlled, as would be the case in an occupied multi-unit residential building, an increase in the variation of standby losses would be expected (Chmielewask et al., 2017; Xue, 2017). Accordingly, this study shows that occupant behavior and inlet water conditions have the potential to negatively influence the energy performance of a building that uses potable water as a cooling medium and where the conditioning of the potable water for occupant use is not an intended benefit for the occupants.

3.4 Conclusions

In this study, the delivered thermal performance for a multi-unit residential system using potable water as the hydronic medium operating under controlled conditions and simulated occupant behaviors was monitored to determine the energy efficiency characteristics of the system as a whole, and to verify the characteristics that are often claimed by proponents to exist. From the observations it is clear that the linear model using steady-state efficiency (η) provides a good fit throughout the operating loads of the system and that using potable water as a hydronic medium result in steady-state operating efficiencies over 90%.

The use of potable water as a hydronic cooling medium was not found to be as attractive as its use as a heating medium. While the linear model approach does fit the data, it was determined that the inlet water temperature had a significant impact on the idle losses for the system. As a result, the use of potable water as a cooling medium should be limited to areas where the ground water temperature is less than the target temperature for circulation. This limitation would prevent the installation of such systems throughout the majority of the major populated areas of North America, but it would still be viable for northern climates where water distribution temperatures are well known.

CHAPTER 4: TECHNIQUES for MEASURING PALITABILITY and PERCEPTION of WATER

4.1 Introduction

Occupant perception of the quality of drinking water is a major concern for many in the water industry (Doria, 2010; Webber et al., 2015; Kelly et al., 1997). While palatability changes in cold water due to circulation and age are minimal (AWWA, 2002; Ammerican Water Works Association, 2005), the effects on heated service water have not been well documented. As the majority of potable water used in a residential occupancy is hot service water (Xue et al., 2017; Chmielewska et al., 2017), and that water is primarily used in processes that bring it into close contact with the occupants, there is a need to know if the storage and circulation of hot service water will impact the occupants perception of the water.

4.2 Impacts of Construction Materials on Water Quality

There are a number of means to influence the quality of potable water by its storage and use. This well researched area is a major concern for the water utility industry. The primary means of altering water quality include chemical leaching from materials in contact with the water, chemical reactions of materials in the water, and biological activity (Burlingame et al., 2007). Careful selection of piping and construction materials is required to minimize the potential to alter the water quality when working with potable water, and the materials used is this experiment were specifically selected for their compatibility with potable water (Heim, 2006).

4.2.1 Chemical Leaching

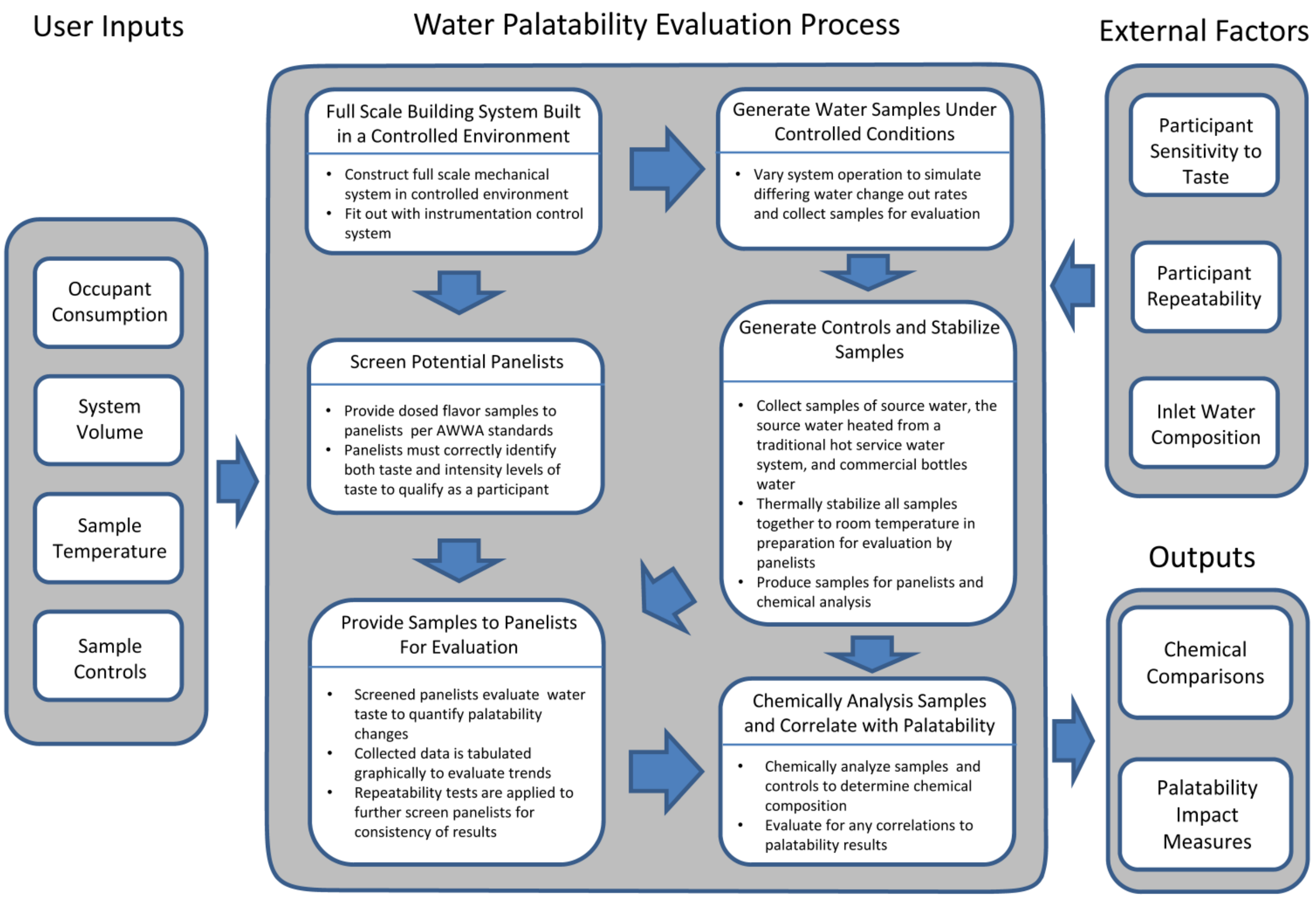
Often, pipes and construction materials will provide a means to introduce chemicals to potable water that results in a deterioration of the water quality. This can be through materials chemically leaching into the water from metallic (Sorlini et al., 2014) or polymer construction materials (Whelton et al., 2010; Ryssel et al., 2015; Holsen et al., 1991) or through corrosion of the construction materials (Masters et al., 2015; Munn, 2017; Rushing et al., 2004; Lytle et al., 2010). The pursuit of making building more environmentally friendly has resulted in new construction materials being introduced to the market that introduce new chemicals to potable water, and the full material compatibility with potable water is not understood (Kelley et al., 2014).

4.2.2 Chemical Reactions

Many chemical reactions alter the quality of potable water. Disinfectants used to counter biological activity can deteriorate, there can be interactions between chemicals in the water, and the construction materials of the system (Becker, 2002; Chung et al.; Casteloes et al., 2017).

4.2.3 Biological Activity

Another means for the quality of water to deteriorate is through biological activity in the water. While the protection of most potable water systems from biological decay is through the addition of a disinfectant, pathogens can survive (Biyela, 2010; Inkinen, et al., 2014). The type of microbiome that can establish itself is often a factor of the local utilities sanitation techniques



Full Scale Building System Built in a Controlled Environment

- Construct full scale mechanical system in controlled environment
- Fit out with instrumentation control system

Generate Water Samples Under Controlled Conditions

- Vary system operation to simulate differing water change out rates and collect samples for evaluation

Screen Potential Panelists

- Provide dosed flavor samples to panelists per AWWA standards
- Panelists must correctly identify both taste and intensity levels of taste to qualify as a participant

Generate Controls and Stabilize Samples

- Collect samples of source water, the source water heated from a traditional hot service water system, and commercial bottles water
- Thermally stabilize all samples together to room temperature in preparation for evaluation by panelists
- Produce samples for panelists and chemical analysis

Provide Samples to Panelists For Evaluation

- Screened panelists evaluate water taste to quantify palatability changes
- Collected data is tabulated graphically to evaluate trends
- Repeatability tests are applied to further screen panelists for consistency of results

Chemically Analysis Samples and Correlate with Palatability

- Chemically analyze samples and controls to determine chemical composition
- Evaluate for any correlations to palatability results

Figure 4.1: Process methodology to evaluate changes in potable water palatability

and the materials used in the construction of the system (Ji et al., 2015). As the apparatus will be maintaining a water temperature at or above the water temperature recommendations to minimize biological activity in the hot water side of the system (Stout et al., 2004; Cooper et al., 2004) biological activity will be investigated, but not expected to be impactful in the palatability tests.

4.3 Flavor Testing Techniques

There are a number of techniques to evaluate the perceptions groups of people have to their potable water. A number of different sensory evaluation methods investigated included Flavor Threshold Testing, Flavor Rating Scale, and Flavor Profile Analysis (Bruvold et al., 1989). As the intent is to establish perceptions to the quality of water, the Flavor Profile Analysis (AWWA, 2012; Durand, 2013; Khiari, 2004) technique was selected. This technique utilizes a semi-quantitative scale in conjunction with a water taste and odor wheel (Suffet et al., 1999) to establish a taste intensity rating. Screened panelists needed instruction in how to perform the analysis and record their results (ASTM Committee E-18, 1981; Bartels et al., 1987; American Water Works Association, 1993). The addition of ongoing screening to the selection procedure for the panelists evaluated repeatability and consistency in their responses. While not required in a flavor profile analysis, repeatability testing is part of the flavor rating scale selection process. Ongoing screening was included to improve the confidence that the panelists were providing consistent data (Bruvold et al., 1989). Screening procedures, and testing parameters are included in Appendix B for reference. Working with panelists required approval form the University of Alberta Research Ethics Office, which has been included in Appendix C for reference.

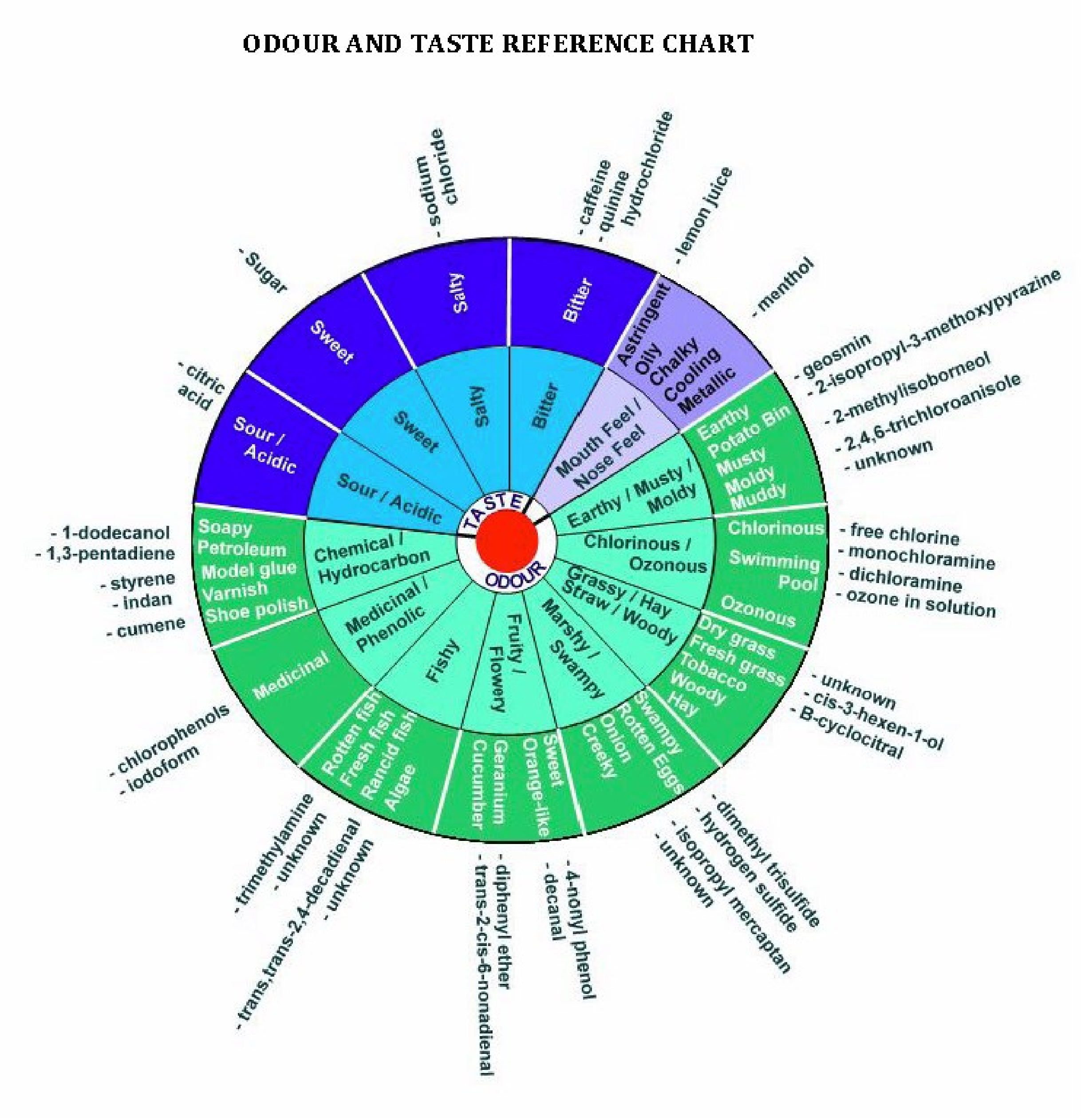


Figure 4.2: The taste and odor wheel (Suffet, Khiari, & Bruchet, 1999)

4.4 Screening and Testing Procedures

Screened panelists utilized the technique identified in Standard Method 2170 B-FPA (AWWA, 2012). In this technique, each potential panelist is provided with 12 blind samples of drinking water that have been dosed with specific mass concentrations of flavoring to provide three different intensities of each of the four main flavors. Citric acid is used for sour (0.05%/0.10%/0.20%), sugar is used for sweet (5%/10%/15%), salt is used for salty (.4%/.7%/1.0%), and caffeine is used for bitter (0.05%/0.10%/0.20%). Participants must correctly identify each flavor (with no errors), and each intensity (one error is permitted) to be eligible to participate. Additionally, during the analysis period, repeatability screening occurred by providing samples containing water from an identical source. The panelist reporting for these samples needed to be within the threshold of detection or the panelist was not reliable and their data excluded from the analysis (Elmaci et al., 2007).

During the analysis period, samples were collected in accordance with the flavor profiling analysis specifications as outlined in Standard Method 2170-B (AWWA, 2012). All samples were collected the day prior to the meeting of the panelists, stored in glass containers with custom glass closures, and immediately refrigerated to stabilize the samples at an identical temperature. The next day, the samples stabilized together in a water bath until they were all ~25°C (77°F). The panelists reviewed these samples.

The analysis period was comprised of two times. The first analysis period was from February 2015 to April 2015, and included the input of a single panel comprising of 3-4 individuals. The panel met weekly and collected data each week to generate a single data point. The second analysis period was from January 2016 to April 2016, and included 3-4 panels of four individuals who met weekly. Each panel generated a single data point in accordance with Standard Methods 2170-B (AWWA, 2012) allowing 3-4 data points to be generated for each water sample tested that week. Utilizing two sets of panels allowed for both the opportunity to refine the logistics of coordinating the panel meetings as well as providing different data sets that can be compared independently.

During each meeting, four randomized water samples was provided to each panel, apparatus water, cold water from the apparatus supply, hot water from a traditional system supplied by the same cold supply, and bottled water. The samples randomized for each panel so discussion is limited to internal panel members. Each panelist reports the intensity of the flavor of the sampled water as well as a flavor descriptor (the descriptor is not part of the data collection but is included as a means to promote internal discussion per Standard 2170-B). During the data analysis, each reported flavor intensity is recorded as a difference between the apparatus water and the cold supply water, then the results from each panel member are averaged together to generate a single panel reported data point.

4.5 Data Analysis

Traditional hot water and cold source water were reviewed to evaluate if chemical changes as a result of simply heating the water would affect the result and it was determined that there was no impact to the reported flavor intensity as a result of heating the water. Chemical analysis of the water samples identified that the chloramines added to the water as a disinfectant did degrade to chloride and ammonia in the traditional hot water sample, but this did not result in a palatability impact during the flavor profile analysis. The apparatus water exhibited a similar degradation of the chloramine, but since degradation was not a cause to any changes observed, as it does not affect the palatability.

The controlled variable in this study was the rate of water usage by the simulated occupants in the building. As the occupants utilize more water, there is more change out of the water in the system. The reported age of the water in the system is a ratio of system volume to water consumption rates. For this study, this is the consumption ratio, which is a relative age of the water in the system, and if the volume consumed per day is used, the consumption ratio (Cr) will have a unit of days.

By plotting the change in reported intensity of taste between the apparatus samples and cold source water against the consumption ratio, there was a clear increase in taste intensity as the consumption ratio (Cr) was increased. The results, as published in Chapter 5, do not show that the taste became objectionable to the panelists for the range of consumption ratios tested, but a change was noticeable and identifiable for consumption ratios of several days. Presentation of the data from the 2015 analysis with the data from the 2016 analysis shows the fit of the two data sets is within the threshold of detection. This would reinforce the inference that FPA can be conducted using small groups of panelists and still produce useful results (AWWA, 2012).

4.6 Future Work

The chemical analysis of the apparatus water eliminated many potential pathways for the change in occupant perceptions. While the chloramine used as disinfection agent had degraded to ammonia and chloride, a similar degradation in the non-apparatus hot water did not result in perception changes amongst the panelists. Most physical properties, such as pH, Total Dissolved Solids, and hardness were unchanged between the samples. Where there were significant changes was in the concentration of ions and dissolved metals, many increased concentration quickly, stabilizing, and not exhibiting a correlation with the flavor impact due to increasing consumption ratios. Five metals did have concentration trends that correlated with the flavor impacts: Boron, Cadmium, Lithium, Cobalt, and Zinc. These are metals used in the manufacture of plumbing components, particularly brasses and bronzes. While taste threshold data is incomplete when addressing mineral content, there are some established thresholds. Cadmium and Boron do not influencing taste when introduced to water (Agency for Toxic Substances and Disease Registry (ATSDR), 1989; United States Environmental Protection Agency Office of Water Health Advisories, 2000). Zinc has a taste threshold of ~4 mg/L (Health Canada, 2018), and Lithium as a salt has a taste threshold of ~140 mg/L (American Society for Testing and Materials, 1978), far above the concentrations observed during this analysis. Individually these metals would not be responsible for the changes in flavor. Cobalt currently does not have information available regarding flavor thresholds (Federal - Provincial - Territorial Committee on Drinking Water, 2009). Due to the extensive use of these metals in domestic plumbing systems, it would be of value to investigate their effects on water flavor, either individually (for cobalt), or in combination.

CHAPTER 5: EXPERIMENTAL STUDY into PALATABILITY IMPACTS of POTABLE WATER as a HYDRONIC MEDIUM[2]

5.1 Introduction

It is common for multi-unit residential buildings to be constructed utilizing a central heating plant to provide for the servicing requirements of the building. Buildings that utilize a central system will typically employ multiple systems and distributions due to the different servicing needs for the suites, which can include heating water, potable hot service water, potable cold service water, and chilled water. It is not unusual for these systems to be installed using completely separated piping systems, even though similar materials are being transported. This will result in the installation of multiple piping systems which convey similar materials intended for differing purposes, specifically hot water for building heating and hot service water for occupant consumption. Piping can be combined into a single distribution system able to fulfill the requirements of both uses, provided that all local codes and safety standards for heating using potable water have been met.

The technique of using potable water as a hydronic medium in multi-unit residential buildings involves the utilization of heated service water as the thermal transport medium for conditioning the building environment under heating conditions. In what is often referred to as an “integrated piping system” (Butcher, 2007) or a “combination system” (ASHRAE, 2011), hot service water is delivered to the heated zones using the potable water distribution system that has been installed within the building. A portion of the water is used by the occupants as part of consumption for daily activities, while the remaining portion is recirculated back to a central

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[2] The manuscript appearing as Chapter 5 of this thesis was published in the February 2018 edition of *Water (MDPI),* at the time of publication of this thesis.

plant after being utilized to condition the space. While the concept of using potable water as a heating medium in single-family dwellings has been investigated in a number of research studies (Caron et al., 1983; Subherwal, 1986) with a number of documented advancements in efficiency, the investigation and implementation of this technique in multi-unit residential buildings has been limited. Due to this lack of investigation there have been concerns raised about the implementation of these systems from both performance and safety standpoint (MacNevin, 2016; Canadian Institute of Plumbing and Heating 2008).

One major concern explored within the present research is that the utilization of potable water for HVAC may alter the water, due to trace materials in the water being exposed to cycles of heating and cooling or due to leaching into the water from the system materials, which would result in tastes or odors that occupants would find objectionable (Whelton et al., 2010; Kelley et al., 2014; Venere, 2014; Marrow, 2017). Given that taste and odor are considered two of the most important criteria for potable water systems (Loganathan et al., 2006), and are often used as an indicator of water safety (Kelly et al., 1997) this is of interest to designers and manufacturers.

The present research describes an experimental design constructed to simulate a full-scale, multi-unit residential building through which water samples are generated to represent a range of simulated occupant behaviors. By altering the daily consumption of the simulated occupants, the retention duration of the water within the system was varied. This permits the generation of samples with retention times or consumption ratios (Cr, the ratio of system volume to daily occupant consumption) which are larger than those commonly encountered outside a controlled environment. Collected samples were presented to a group of trained panelists, who tested and rated the samples in accordance with the Flavor Profile Analysis (FPA) procedure provided by the American Water Works Association (AWWA, 2012). Flavors and intensities are tabulated and compared to determine if any tastes reported in the samples are attributable to the residence time of the water in the HVAC system.

5.2 Materials and Methods

5.2.1 Experimental Design

To effectively study the impacts on the palatability of potable water of implementing potable water heating distribution in a building, a potable water mechanical system was constructed in a controlled environment which would be used to generate water samples for analysis. The completed system was modeled after a 4-unit apartment building in a riser configuration that is capable of delivering heating, cooling, and service water to each unit as depicted in Figure 3.1. The author selected the riser configuration for this case given it is representative of many low-rise residential buildings that are constructed with a central heating plant. Water is plumbed from the central plant to each suite, where it can be delivered to the unit's plumbing fixtures or circulated through a potable-rated fan coil (heat exchanger) and returned to the central plant for re-conditioning. All components utilized in the construction of the apparatus are rated for use with potable water, and all piping in the apparatus constructed was configured in a manner that permitted circulation of all components every 24 hours in accordance with local codes (Canadian Standards Association, 2012) to prevent stagnation. The apparatus is controlled by a programmable logic controller (PLC), programmed to operate heating cycles and to simulate occupant activities that consume potable water. The materials utilized in the construction of the apparatus include PVC for cold water distribution, CPVC for hot water distribution, PEX tubing for terminal unit connections and fixture connections, copper inside the fan coils, and brass and bronze fittings. This is significant as many of these materials have been tested for palatability impacts individually (Kelley et al., 2014; Heim et al., 2007; Heim et al., 2006); there has not been a study of a completed system using these materials in conjunction.

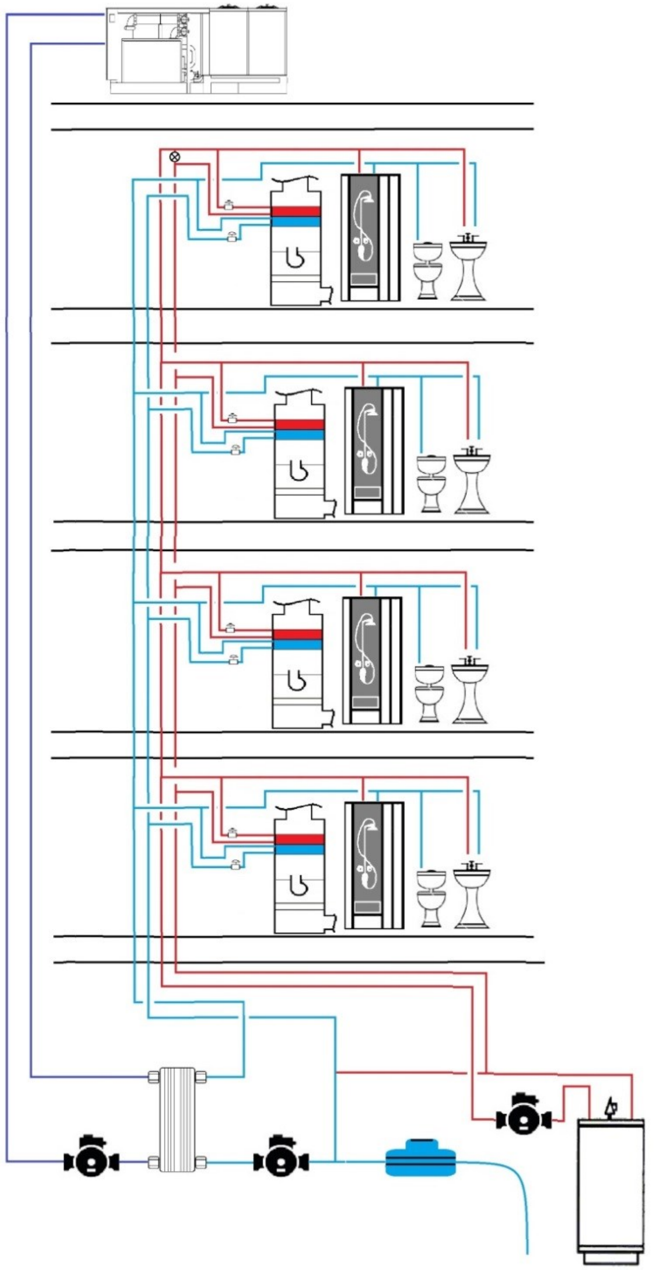


Figure 5.1: A schematic representation of the potable water HVAC apparatus constructed to generate samples. Apparatus includes four independently controlled 4-pipe fan coils, four suites distribution headers, one hot water generator, and one chilled water system.

5.2.2 Water Palatability Test Protocol

The desirability of water is governed largely by taste, a subjective trait which can be difficult to quantify. Since the evaluation of the palatability of potable water is routine for the municipal water works industry, AWWA has developed a set of procedures referred to as “Standard Methods”, which includes Standard Method 2170 B–FPA (AWWA, 2012). Standard 2170 B includes the procedures for conducting a Flavor Profile Analysis (FPA) and has been used successfully for establishing flavor characteristics and associated intensities in water samples (Wiesenthal, 2007). According to the outlined standard methods, the FPA utilizes a group of screened panelists, 4 to 6 per panel visit in this study, to evaluate samples of water and provide a single description and intensity for each sample. Intensities are assigned a numerical value by each panelist in accordance with the FPA procedure, ranging between 0 (no taste) and 3 (objectionable, not drinkable) in 0.25 increments (threshold of detection per FPA), providing a quantitative measurement for flavor. An intensity of less than 1 (but greater than 0.25) is considered to be noticeable, but not objectionable, and an intensity of 1 or greater is considered to have the potential to be objectionable. Screening and training of the panelists includes the testing of volunteers for the ability to distinguish taste and intensity of pre-determined flavor samples in accordance with Standard Method 2170 B.

Once the panelists have been selected, additional screening is conducted throughout the experiment to evaluate the panel members’ consistency when evaluating tastes. This is done by conducting flavor profile sessions where apparatus test samples are not provided and identical source water samples are included in the sample set. The data collected from participants who report a variation beyond the threshold of detection in these samples as provided in the procedures for Standard Method 2170 B are excluded from the analysis. This extra level of screening is above the prescribed requirements of Standard Method 2170 B, but was considered valuable for maintaining the consistency of the results.

Previous investigations into water palatability have encompassed issues such as the effects of the water's age on active municipal distributions (AWWA, 2002), and the use of FPA to study the effects of piping materials on the palatability of potable water (Heim et al., 2006). In each study, the effects on palatability of the reviewed variable have been found to be minimal under the operating conditions adopted in the present study, when the age of circulated cold water as well as certain piping materials in the cold water system are not considered among the uncontrolled variables. Accordingly, this study focuses on the potable hot water used in the system.

A total of four samples is provided in random order for each evaluation meeting to prevent any bias by the participants and to provide a variety of samples:

1. Apparatus water
2. Potable cold supply water from the municipal supply feeding the apparatus
3. Potable hot water from an adjacent, traditional source
4. Commercial bottled water (Nestle Pure Life purified water)

While the apparatus water and the cold supply water are the samples of interest, control samples from other sources are provided to allow for additional comparisons to identify possible causes for flavor variations. Each sample is collected at the same time from the service water discharge of the apparatus and thermally stabilized in accordance with Standard Method 2170 B to 25°C. The four samples are evaluated by the panel and the results are compared to determine if there are any effects which could be attributed to the use of potable water for heating purposes.

In addition to the samples collected for the FPA, additional samples of Apparatus Water, Potable Cold Supply Water, and Potable Hot Supply Water are collected for laboratory analysis to identify potential chemical alterations which would be correlated to any reported FPA results. While this does not provide definitive proof of cause of the flavor alterations, it allows for certain variations to be eliminated as probable contributors.

To evaluate the repeatability of the tests, the panel tests are repeated again after one year with the same apparatus and different panelists. While participants are allowed to volunteer for both sets of evaluations, the screening and recruitment process was completely repeated in full to encourage different individuals to participate in the panel study. The first panel test includes a single panel of volunteers which meets on a weekly basis for approximately three months. The second panel test expands the volunteer group to include three to four panels of four volunteers each which meet weekly for approximately three months.

5.2.3 Apparatus Samples

Throughout the FPA, the dependent variable is the descriptor intensity provided by the panel, between the water samples generated by the experimental apparatus and the water samples derived from the feed water supplying the experimental apparatus. The independent variable is the consumption ratio (Cr) of the experimental apparatus:

$$Cr = S_v / O_c \qquad [5.1]$$

Where:

Cr = Consumption ratio (days)

S_v = System volume (gallons)

O_c = Occupant daily consumption (gallons/day)

In this equation, the consumption ratio (Cr) refers to the representation of the variable being investigated; the system volume (S_v) refers to the volume of the distribution system including all vessels, pipes, and fittings; and the occupant consumption (O_c) refers to the volume of water consumed by the simulated occupants each day.

All samples were collected one day prior to the panel meeting. The samples are then temperature stabilized and held in the same location in order to eliminate any variations in temperature or environmental impacts that may generate undocumented variations between the samples.

In existing multi-unit residential potable water heating distributions, it should be noted that consumption ratios of less than one, where the daily consumption by occupants (O_c) is greater than the volume of the distribution system (S_v), are typical, with the authors being aware of no reported palatability concerns. Samples with consumption ratios greater than 1 are thus considered in this study. Elevated consumption ratios (Cr) are possible in practice due to the large system volumes present in multi-unit residential buildings and low consumption, either due to water-efficient design or low occupancy. To generate the samples, the experimental apparatus is allowed to operate automatically for time periods of no less than one week per unit of consumption ratio (Cr) to simulate long-term operation. Due to the time required, samples are limited to consumption ratios ranging from 1 to 7.

5.3 Results and Discussion

5.3.1 Palatability Results

While the intent is to compare the reported flavor of the apparatus water to the source supply in order to investigate alterations, other observations are identified during the FPA studies that provide insight into understanding the causes of the flavor alteration. First, any flavor variations between the cold supply water and the bottled water control samples (sample item 2 and sample item 4) are reported by the panels to be below the threshold level. This is consistent with prior research into tap water and bottled water flavor comparisons (Teillet et al., 2010). Second, any flavor variations between the cold supply water and the potable hot water samples (sample item 2 and sample item 3) are also reported by the panels to be below the threshold level. This is significant, as any chemical variations between sample 2 and sample 3 can be eliminated as sole contributors to variations in sample flavor.

In regards to the comparisons between the apparatus water and the cold supply water samples (sample item 1 and sample item 2), the most commonly reported descriptors among the panel groups are found to be chlorinous, chalky, and bitter. Given that the variable being measured is the change in intensity of flavors between the apparatus water and the supply water, the numerical representation of the intensity of any flavor reported for the supply water is removed from the intensity of any reported flavor of the apparatus sample; the resulting intensities for each panel group are compiled and shown in Figure 5.2. From the resulting intensities, consumption ratios in excess of 1 indicate changes in the perceived flavor of the water beyond the accepted threshold of detection. While reviewed consumption ratios as high as 7 are found to result in noticeable changes to the intensity of reported flavors, under none of the consumption ratios tested does the panel report that the change in flavor is in the objectionable range. Additionally, both panel tests produce results which are similar in outcome, which implies that a similar mechanism is affecting the palatability of the water independent of the time elapsing between tests.

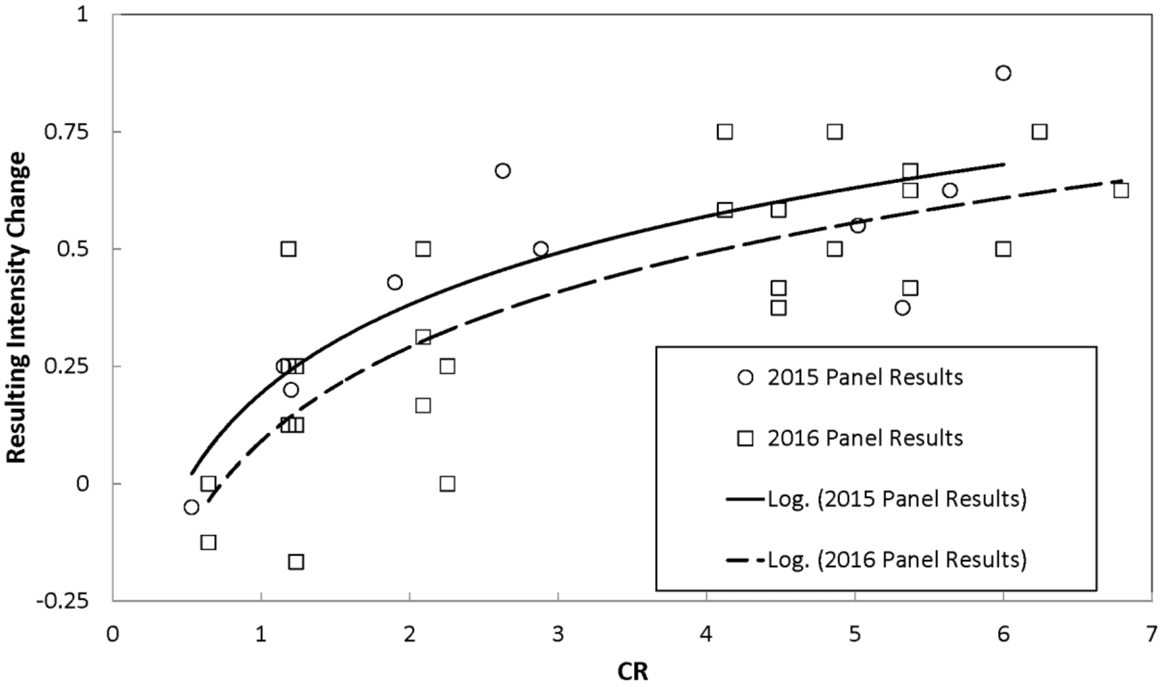


Figure 5.2**:** Changes in panel recorded taste intensities between apparatus samples and source water samples

5.3.2 Chemical Analysis Results

Samples are collected for chemical analysis to review potential changes in the chemistry of the water that could hypothetically contribute to the panelist perception of the water.

Chloramines/Chlorine. Chlorine is not found in any of the analyzed apparatus water tests. There is a consistent measured increase in chloride and ammonia for all collected samples, which suggests that the total chlorines have reduced to simpler components as shown in Table 5.1. This is not unexpected, as it has been previously indicated that heated storage with recirculation will reduce the chlorine content and promote the formation of disinfection by-products (Liu et al. 2015). The potential contribution to the palatability is minor since the reduction in chlorine presence was found to be absolute for all CRs rather than correlated with reported intensities.

pH, conductivity, Alkalinity, TDS, Hardness, Nitrate/Nitrite. All samples report minimal changes between the cold source and apparatus samples for the above-identified parameters as depicted in Table 5.1. The significance of these changes is questionable as the variation in measured readings among the cold source samples varies more significantly through the test period than the difference between the cold supply samples and the apparatus samples for any individual test.

Table 5.1**:** Chemical results which did not exhibit material chemical changes due to the apparatus or expected changes which were shown to not impact the palatability results

	Detectable Limit	Units		Source Water Average Chemistry	min	max		Apparatus Water Average Chemistry	min	max
Chloramines										
Chlorine, Free	0.1	mg/L		0.468	0.1	0.74		0	0	0
Chlorine, Total	0.1	mg/L		1.116	0.13	1.84		0	0	0

Total Chlorine minus Free Chlorine	0.2	mg/L		0.805	0.38	1.54		0	0	0
Ammonia, Total (as N)	0.05	mg/L		0.3296	0.308	0.349		0.4362	0.416	0.453
Chloride (Cl)	0.5	mg/L		5.066	4.78	5.58		5.888	5.59	6.26
Fluoride (F)	0.02	mg/L		0.6712	0.655	0.693		0.759	0.743	0.796
Ion Balance		%		98.28	96.3	99.2		98.22	96.4	99.7
TDS (Calculated)		mg/L		212.8	205	220		208	200	220
Hardness (as CaCO3)		mg/L		168	162	172		162.6	157	173
Nitrate (as N)	0.02	mg/L		0.0498	0.022	0.074		0.0572	0.03	0.079
Nitrate and Nitrite (as N)	0.022	mg/L		0.05675	0.045	0.074		0.0572	0.03	0.079
Nitrite (as N)	0.01	mg/L		0	0	0		0	0	0
Sulfate (SO4)	0.3	mg/L		68.32	64.3	72.1		66.76	64.8	68.9
pH	0.1	pH		8.134	8.01	8.2		8.112	8.08	8.16
Conductivity (EC)	0.2	uS/cm		396.2	384	410		389.2	375	405
Bicarbonate (HCO3)	5	mg/L		140	131	147		135	128	145
Carbonate (CO3)	5	mg/L		0	0	0		0	0	0
Hydroxide (OH)	5	mg/L		0	0	0		0	0	0
Alkalinity, Total (as CaCO3)	2	mg/L		115	108	121		110.6	105	119

Major Ions and Dissolved Metals. While the mass spectrometry tests are testing for the presence of over 40 elemental metals in the water, only a small number indicate a material change in concentrations. Many of the metals, including copper, lead, manganese, and silver, identified a flat increase (where the measured concentration increased relative to the source sample, but the increase was constant for all test and did not vary with consumption ratio) in concentration for all CR tested, which suggests a lack of independent influence on the palatability of the water. This is significant as the study of thermal variation causing thermogalvanic corrosion in copper pipes has been well documented, but it does not appear to be a contributor to alterations in palatability of the potable water (Edwards, 2004). Five elements that were included in the analysis exhibit a measurable increase, which correlates to the CR of sampling; boron, cadmium, cobalt, lithium, and zinc are shown in Figure 5.3 These metals are recognized as present in commonly used plumbing components and the majority of the materials are measured well below acceptable levels, with the potential exception of cobalt. While cobalt is accepted in drinking water without standards in place in most jurisdictions, three U.S. states (Arizona, Minnesota and Wisconsin) have guidelines in place for levels of cobalt in drinking water (FSTRAC, 1995; FSTRAC, 1999). Although they are guidelines and not standards, it should be noted that for longer duration CR values in the present study, these guidelines are found to be approached or exceeded. The measured concentrations are not high by any means (World Health Organization, 2006), just approaching or exceeding the few existing guidelines that are available. The source of the cobalt in this study could be difficult to isolate, although it should be noted that cobalt oxide is used as a binding agent for the glass lining of glass lined storage tanks and water heaters.

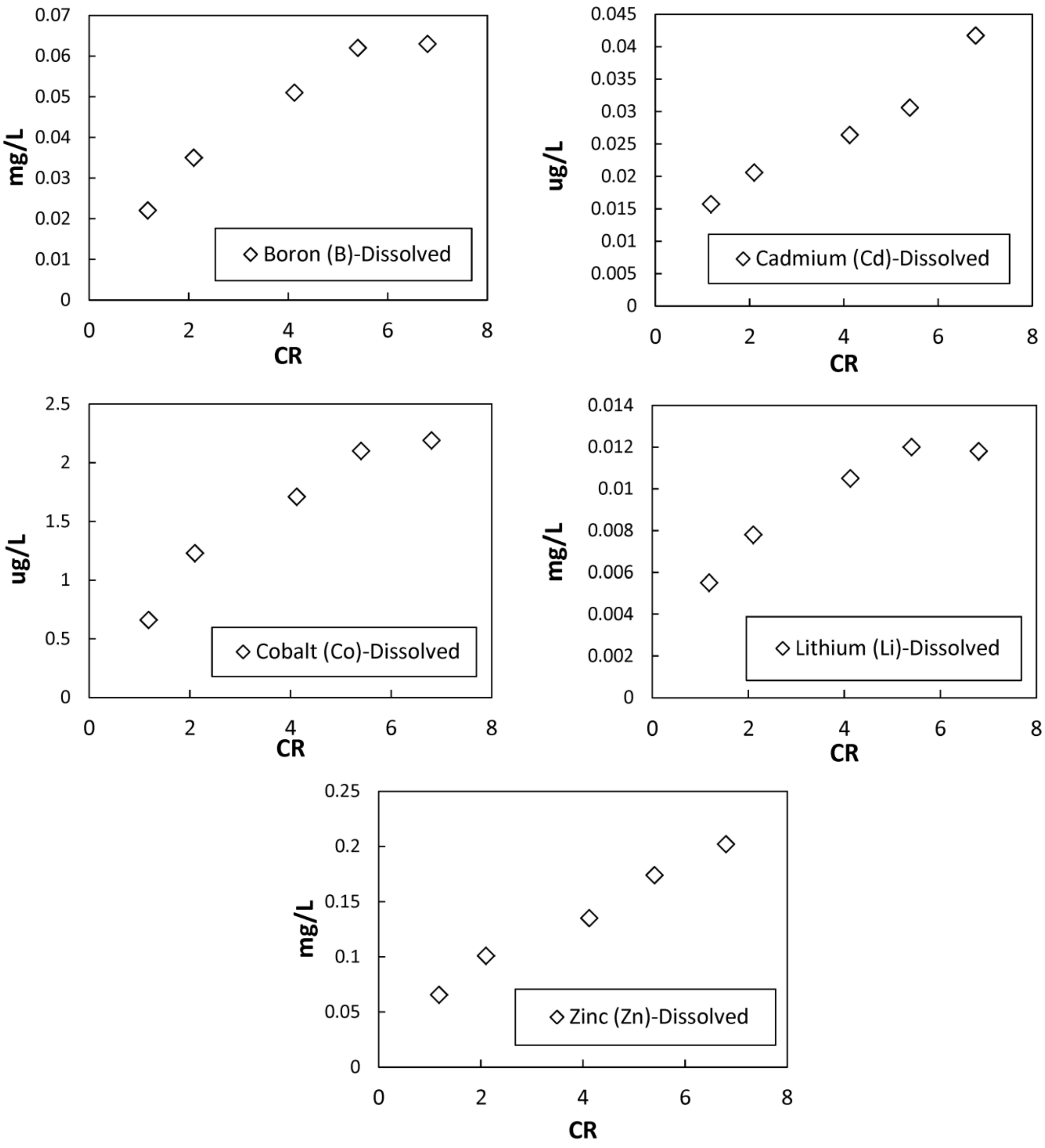


Figure 5.3: Dissolved metal increases relative to consumption ratio

5.4 Conclusion

In a system where potable water was continuously circulated as a hydronic heating medium and not allowed to become stagnant, the perception of the potable water used was not affected to a magnitude to cause individuals to consistently report an unsatisfactory alteration in taste for the range of consumption rations tested. A consumption ratio (Cr) in excess of two was required for consistent reporting of any perceivable change in the taste intensity present in the water samples. Based on these results, it would be recommended to maintain a consumption ration of one or less for systems utilizing potable water as a hydronic heating medium, regardless of the circulation procedures utilized by the system as a whole. Chemical testing was able to identify metallic leaching of specified elements into the system water which did correlate with changes in flavor intensity in the water, and while the concentrations are low, likely contributed individually or in combination to the flavor of the water. Under no consumption ratios did any of the metallic concentrations indicate an unsafe accumulation.

CHAPTER 6: DEVELOPMENT of SENSITIVITY BASED LIFE CYCLE ANALSYIS

6.1 Introduction

Conducting a Life Cycle Cost Analysis is considered a useful means in determining the costs of a building system or component and can assist in making decisions about which systems and components to utilize in a building. In order to perform a Life Cycle Analysis on a yet to be constructed building or a building system, a substantial amount of information can be required. Construction costs, energy use, energy cost, maintenance, and disposal must all be estimated and available prior to starting the analysis. While some of this information can be readily available, such as the current utility rates and average climatic information, and estimates for some, such as the expected construction cost, it is not possible to know all of the required information and the analysis must use some prediction, such as for future costs. As estimations and predictions can comprise a majority of the information, there can be questions about the value of the information derived from a Life Cycle Analysis. As the intent is to use the outcome of the analysis to assist in making a decision about which mechanical systems would be best suited to a building, and specifically in this case, to evaluate how the cost of Open Loop HVAC systems compare to traditional systems over their life, a realistic output is essential. Previously Monte Carlo simulation has been used to evaluate sensitivity of Life Cycle Analysis, it is proposed that the Monte Carlo simulation can be the Life Cycle Analysis, factoring in the sensitivity to inputs to determine which system not only would be most cost effective over the life of the building, but also which system would be least susceptible to market and climatic conditions.

6.2 Required Information

Conducting a Life Cycle Analysis on a system requires a significant amount of information as well as a review of the quality of the data used (Iternational Standards Organization, 2006). This can involve a number of steps (Kaklauskas, 2016; Farr, 2011):

1. Establish what units are measured. This can be a number of items, including, but not limited to, cost and/or emissions.
2. Any embedded units need to be assessed. This can represent cost to install, or could be CO_2 generated through manufacturing and transportation (Hammond et al., 2008; Hammond G. C., 2006).
3. Tabulate units affected by the operation of the system throughout the estimated life cycle. If analyzing costs, this could include fuel and maintenance. Alternatively, if analyzing emissions, then this could be the CO_2 emitted though the consumption of fuel and CO_2 embedded in parts used for maintenance.
4. Determine salvage and/or disposal costs. At the end of the life cycle, there will be a unit value associated with the end of life cycle conditions of the system. If the system has value, this could be a net benefit or a cost if the disposal expense exceeds and retained value.

Breaking down each of these steps results in an activity based costing system (Emblemsvag, 2003; Farr, 2011). In this system, one must independently review each activity in each step, independently tabulating the unit cost associated with that step. In theory, this would be an easy accomplishment with object based simulation software as these packages specifically simulate a task or process as a series of steps.

6.3 Life Cycle Cost Analysis

The fundamental equation for determining the life cycle cost of a system is illustrated in Equation 6.1.

$$LCC = BC + \Sigma(MC + OC) + SC \tag{6.1}$$

where:

LCC = Life cycle cost ($)

BC = Building cost of system construction cost ($)

MC = Maintenance cost ($)

OC = Operating cost ($)

SC = Salvage cost ($)

BC and SC are values that can be estimated using current costs. With regards to maintenance and operations, each individual component is further broken down into individual costs associated with individual time increments that represent the life of the system.

$$MC = \sum_{i=1}^{n} MC_i \tag{6.2}$$

$$OC = \sum_{i=1}^{n} OC_i \tag{6.3}$$

where:

n = number of years of operational life (years)

MC_i = Maintenance costs in an individual year ($)

OC_i = Operational costs in an individual year ($)

These components can be further broken down into monthly time periods.

$$MC_i = \sum_{j=Jan}^{Dec} MC_j \qquad [6.4]$$

$$OC_i = \sum_{j=Jan}^{Dec} OC_j \qquad [6.5]$$

where:

MC_j = Maintenance cost in an individual month ($)

OC_j = Operational cost in an individual month ($)

The monthly maintenance cost is dominated by the costs of labor to maintain the system components and equipment. Operation costs represent the energy and utilities required to fuel the system. This is primarily covered by the use of gas and electricity, although other fuels could be used depending on the system. For our example later in the chapter we will limit the fuels to gas and electricity. Equipment life will also be simulated at 30 years for each system; this could be programmed to be different but as each system has similar expected life spans (ASHRAE, 2015) they are kept the same in this simulation.

Operating costs are determined by using the Heating Degree Days and Cooling Degree Days for each month, and working out the amount of gas and electricity that the system would consume for each heating and cooling degree day. The fuel consumed per unit of conditioning is a property of the individual system and is not location dependent. The fuel consumed per unit of conditioning can be estimated using one of the energy modeling systems that are currently available on the market. Once the quantity of each fuel consumed in each month is known, then this can be factored in with the cost of the fuel to determine the operating cost for the month.

$$OC_j = HDD_j * (Hg_{HDD} * Hg_{\$} + He_{HDD} * He_{\$}) + CDD_j * (Hg_{CDD} * Hg_{\$} + He_{CDD} * He_{\$}) \quad [6.6]$$

where:

HDD_j = Heating degree days in month j

CDD_j = Cooling degree days in month j

Hg_{HDD} = Quantity of natural gas consumed per HDD (Gj)

$Hg_{\$}$ = Cost of natural gas (\$/Gj)

He_{HDD} = Quantity of electricity consumed per HDD (kWh)

$He_{\$}$ = Cost of electricity (\$/kWh)

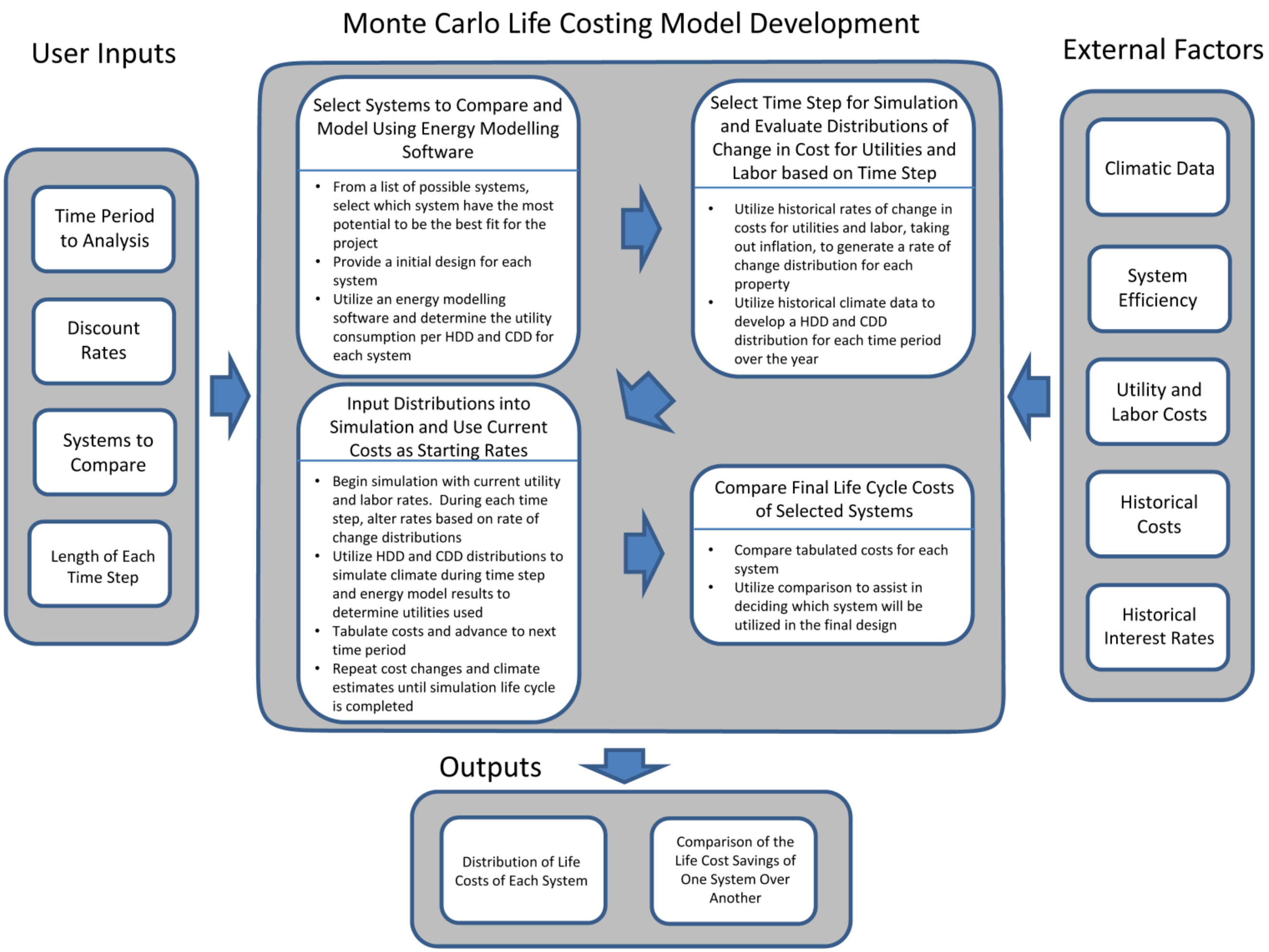
Hg_{CDD} = Quantity of natural gas consumed per CDD (Gj)

Hec_{DD} = Quantity of electricity consumed per CDD (kWh)

Current simulation software used to evaluate energy models and costs typically use a 5-year rolling average to estimate these variables. (Carrier, 2018)

6.4 Problems and Sensitivity

While known information is part of the input used for a life cycle analysis, using prediction and estimation though recent data produces a majority of the information. While there have been a number of techniques proposed to refine the quality of the predicted information (Kaklauskas, 2016), the analysis still relies on potentially unreliable information to produce an output. Sensitivity has become a major consideration for research into Life Cycle Analysis, specifically how to measure it or limit the effects (Liang et al., 2016; Yu et al., 2013; Silva et al., 2014; Yan, et al., 2015; Ross et al., 2002; Saltelli et al., 2000). Unfortunately, the value on conducting Life Cycle Analysis has become questionable as the effects of sensitivity and unknown outcomes become better understood (Buys et al., 2011). Even after many decades of study, many industries have limited understanding or implementation of Life Cycle Analysis (Elnaeim et al., 2017). One item that is being addressed is the sensitivity of Life Cycle Analysis to discount factors. As the analysis can be overly sensitive to the discount factor applied (Copiella et al, 2017), it was not included. The simulation could apply a discount factor to the simulation, applying a predetermined rate to each time cycle, but concerns raised by Copiella identify that the discount factor could artificially reduce the impact of cost volatility. For this analysis, discount factors will not be considered, but it is an area for future investigation.



Select Systems to Compare and Model Using Energy Modelling Software

- From a list of possible systems, select which system have the most potential to be the best fit for the project
- Provide a initial design for each system
- Utilize an energy modelling software and determine the utility consumption per HDD and CDD for each system

Select Time Step for Simulation and Evaluate Distributions of Change in Cost for Utilities and Labor based on Time Step

- Utilize historical rates of change in costs for utilities and labor, taking out inflation, to generate a rate of change distribution for each property
- Utilize historical climate data to develop a HDD and CDD distribution for each time period over the year

Input Distributions into Simulation and Use Current Costs as Starting Rates

- Begin simulation with current utility and labor rates. During each time step, alter rates based on rate of change distributions
- Utilize HDD and CDD distributions to simulate climate during time step and energy model results to determine utilities used
- Tabulate costs and advance to next time period
- Repeat cost changes and climate estimates until simulation life cycle is completed

Compare Final Life Cycle Costs of Selected Systems

- Compare tabulated costs for each system
- Utilize comparison to assist in deciding which system will be utilized in the final design

Figure 6.1: Development process for the Monte Carlo LCA simulation

6.5 Monte Carlo Simulation

Life Cycle Analysis on a building system that is yet to be constructed must be a simulation and Monte Carlo is a means of conducting a simulation (Farr, 2011). Life Cycle Analysis techniques have implemented Monte Carlo Simulation, but it has been limited to evaluating sensitivity of individual inputs, not as the full simulation method (Emblemsvag, 2003; Saltelli et al., 2000). Through the collection of sufficient information, it should be possible to conduct a full Monte Carlo simulation of the cost of a Life Cycle for a specific type of system. As the intent of conducting a Life Cycle Analysis is to assist with making a decision (Cook, 1993), the simulation should compare different systems and identify which one had a lower Life Cycle Cost. During the design process, it is a requirement to select a building system, desirably selecting the system that meets the specification requirements and has the lowest Life Cycle Cost. The actual final Life Cycle Cost is only informative, as it is required to select a system to design a building.

6.5.1 Required Information

The following pieces of information are required to conduct a Life Cycle Analysis of the cost of a building HVAC system:

- Initial construction cost
- Amount of each type of energy required to operate the system during a unit of time.
- The cost of each type of energy.
- The maintenance cost during that unit of time.
- End of life cost or recovery.

As mentioned previously, some of these items can be easy to estimate, the initial construction cost and the present day cost of energy is known or easy to estimate. If the design of the building envelope and specification of the usage is completed, then it is possible to estimate the amount of energy required to maintain the internal environment at set conditions as a function of Heating Degree Day (HDD) and Cooling Degree Day (CDD) through the use of energy modeling software. The energy required based on HDD or CDD is a function of the building, and is not dependent on the climate or location.

The amounts of energy that will be required each month are presentable as a distribution based on the historical weather conditions of each month. Historical weather conditions are readily available for most areas and the historical HDD and CDD of a specific location are presentable as a distribution. As the energy required per HDD and CDD are known and constant, the weather distribution is translatable into an energy consumption distribution. Reported monthly, there is no relation between the weather experienced in subsequent months, so each month has an independent distribution for energy consumption. By utilizing the historical distributions as opposed to an average, the potential for extremes is implemented and the potential for a sequence of extremes can be included in the output.

The distribution for the cost of the energy consumed is different from the weather. While there is historical information on the cost of various forms of energy, a number of factors prevent the translation of historical cost information into a distribution.

- The distribution of historical cost is not random from one month to the next. The cost of energy in one month to the cost in the previous month is related. The cost will change, but it is not randomly distributed.

- Inflation and currency value changes have affected the cost of energy and a simple distribution of historical costs does not reflect this.

By developing a distribution of the derivative of the costs of energy as opposed to a distribution of the cost itself will address these limitations. Extracting the monthly change in cost from the historical cost data provides the monthly cost derivative. Knowing the historical inflation during these same times and deducting the influence of inflation from the monthly cost derivative produces the actual derivative of the cost for that time period, as shown for natural gas in equation 7.7. When the derivatives are collected as a whole, it produces a distribution of the derivative of the cost of energy. With a known current cost, this establishes a potential future cost during any future time, independent of inflation while still allowing trends in costs to occur.

$$\frac{dHg_{\$}}{dt} = \frac{Hg_{\$j} - Hg_{\$\mathrm{j}-1}}{Hg_{\$\mathrm{j}-1}} - INF_j \qquad [6.7]$$

where:

$\frac{dHg_{\$}}{dt}$ = Derivative in price of natural gas between months (%)

$Hg_{\$\mathrm{j}-1}$ = Price of natural gas in previous month ($)

INF_j = Inflation rate for the specific month investigated (%)

Electricity and maintenance costs are modeled the same way. Modelling maintenance costs using the same principal produces a means to set future maintenance costs. As a substantial component of maintenance is labor, modelling the cost of maintenance using the current cost of labor rates, and adjusting them the same way the model adjusts energy costs.

As the model does not consider inflation, the end of life salvage/disposal costs are equivalent to the present day costs.

6.5.2 The Simulation

Once the collection of the required information is complete and the historical data converted into a set of distributions, the simulation is executed. The simulation uses object based simulation software where the object is the total cost of the mechanical system. The building that the system is to be considered for is modelled using a readily available energy modelling package to estimate the energy required (in our example: natural gas and electricity) to maintain internal conditions for each HDD and CDD. The object is assigned an initial construction cost at the beginning of the simulation, along with initial costs of energy and labor, and then progresses through a series of activity steps representing discreet periods of time (months).

During a step, two activities occur: modifying costs based on the cost differential distribution and predicting weather conditions, then the operating cost is calculated and added to the present day life cycle cost of the system. As we are comparing two systems, and assigning an object to each, each object moves through the simulation in parallel so each experiences the exact same weather and economic changes during each run of the simulation. The objects progress through the simulation for a set number of time periods (30 years in the example), after which it is considered to be at the end of life and the salvage/disposal cost is applied to the present day life cycle cost of the system. At this point, the comparison if completed of the total present life cycle cost of each system. As a Monte Carlo simulation, repeating the simulation generates a different set of results, and in the example, conducting the simulation through 100,000 repetitions to generate the distribution of results.

6.6 The Example

Chapter 7 executes a couple of examples on how the simulation would be used to assist in deciding which system would have the lowest present value life cycle cost for a building. The building is an existing 39-unit apartment building located in Edmonton, Alberta. The design specification was readily available for this building, making it well suited to use in an example. The historical inflation, utility, labor, and weather data are also readily available.

6.6.1 Volatility of Costs

The novelty of this method is that cost volatility is a consideration for the output. Figure 6.1 depicts the historical cost of natural gas. Figure 6.2 illustrates the distribution of the differential of the cost of natural gas, developed from the post inflation costing data.

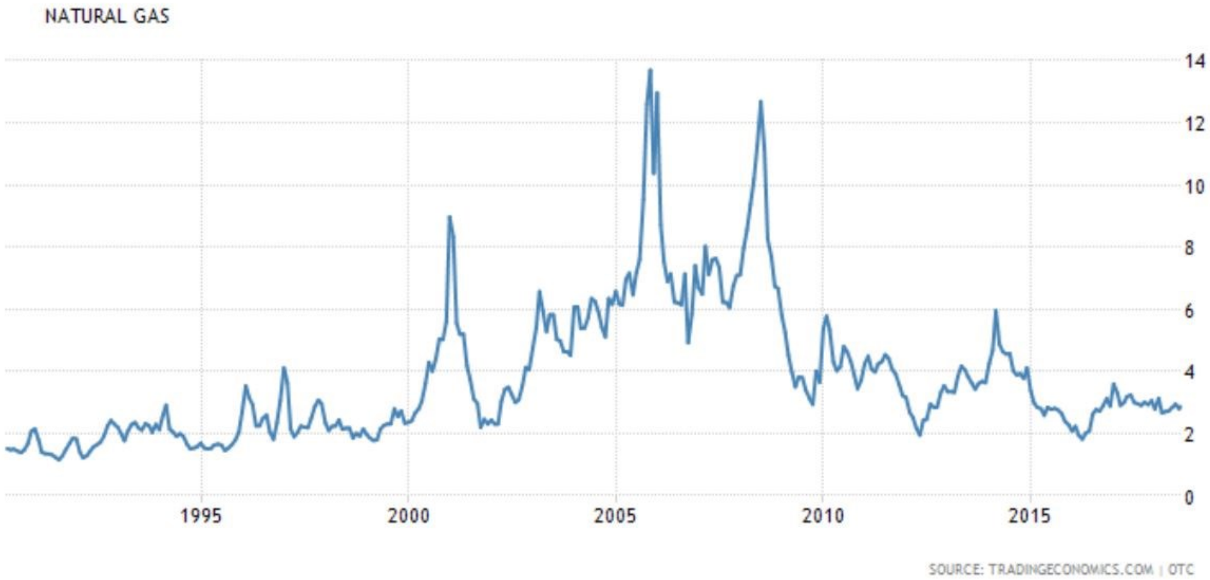


Figure 6.2: The historical cost of natural gas in CAN$ per GJ

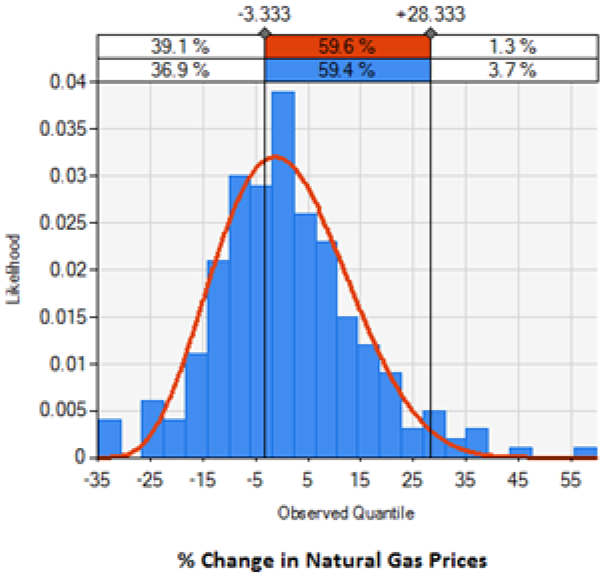


Figure 6.3: The monthly volatility in the price of natural gas discounting inflation.

Comparing the volatility of natural gas to the volatility of electricity, shown in Figure 6.3, identifies that the price of natural gas is more volatile than the price of electricity. It would be inappropriate to conduct a life cycle cost analysis using a set price for natural gas when the price routinely fluctuates by 25% or more on a monthly basis. Including this volatility as part of the analysis produces a more realistic output. Producing a similar distribution for the cost of labor provides the price fluctuation in the cost of maintenance.

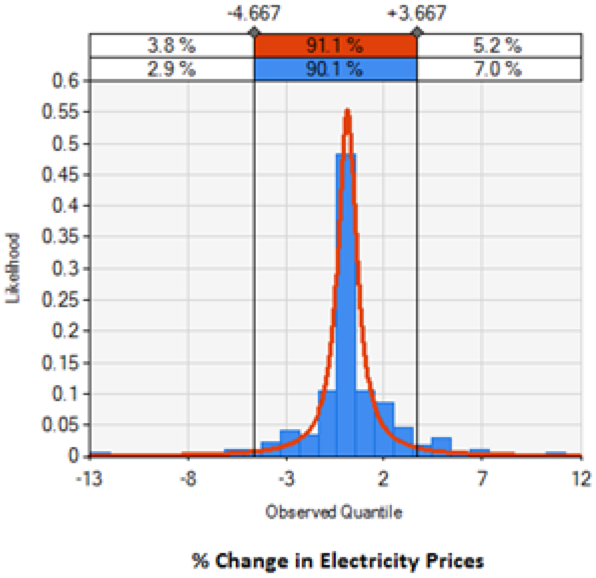


Figure 6.4: Volatility in the price of electricity discounting inflation

6.6.2 Output

Programming the distributions into the simulation and operating a substantial number of simulations produces the curves outlined in Chapter 7. The first comparison was between a high-temperature fan coil system using a modern non-condensing boiler and a heat pump system utilizing a condensing boiler. Both systems used equipment performances found on modern appliances, with the non-condensing boiler performing with 85% steady state efficiency and the condensing boiler performing with 98% steady state efficiency. Concerning the source of thermal energy, heat pumps use a blend of electricity and natural gas as the source, while the thermal energy for the fan coils is functionally exclusively natural gas sourced.

The output curve for the first comparison depicted that there was a slight benefit to the overall life cycle cost by utilizing fan coils. However, when the heat pump system exhibited a lower life cycle cost it did so with a much greater difference in price. Hypothesizing that this is a result of the volatility of natural gas causing a detrimental effect on the operating cost of an exclusively natural gas sourced system. Utilizing a decision tree, even though the fan coil had a slightly higher probability of a lower life cycle cost, the higher difference in price when it didn't caused the heat pump system to be more desirable. If the volatility of natural gas were not considered, then the fan coil system would have been identified as the desirable system.

The second comparison was between heat pump system equipment with a condensing boiler and a fan coil system also supplied with a condensing boiler. One of the characteristics of an open loop HVAC system is that hot service water is limited to a lower delivery temperature so condensing appliances are more practical than non-condensing. The resulting output curve identified a measurable reduction in the life cycle operating cost of the fan coil system, enough to offset the volatility of the cost of natural gas when compared to a heat pump system using a decision tree analysis.

6.7 Conclusion

Criticism towards the value of life cycle cost analysis focusses on the difficulty to collect all the required information and uncertainty about the validity of the output. Using object based Monte Carlo simulation, the variability of weather, the properties of the building envelope, and the differential of the historical costs of operations, it is feasible to model a building system that accounts for pricing volatility. Factoring the volatility of costs into the model can result in identifying a different option as desirable when comparing multiple systems. This approach could avoid future scenarios where economic volatility has negatively affected past building system decisions (Rees, 2016).

CHAPTER 7: OBJECT-BASED LIFE CYCLE SIMULATION as a DECISION TOOL for the SELECTION of BUILDING MECHANICAL SYSTEMS [3]

7.1 Introduction

Selecting mechanical systems in buildings can be a difficult task for designers and developers, as there are many different factors and competing objectives to consider. Using the techniques detailed by ASTM for conducting a life cycle analysis on a building system, it is possible to identify the life cycle costs of a building system and use this information to make decisions as to which system would be preferable for implementation in a given building project (ASTM International, 2013). However, the standard techniques for conducting a life cycle analysis necessitate manually setting values for escalation rates of utilities and energy consumption. ASTM does recognize that Monte Carlo simulations are a valid technique for estimating the sensitivity of the final results to variations in the set variables (ASTM International, 2015), but the standard practice is still to conduct the models using fixed values. Given that a building is subject to varied weather conditions, price fluctuations in fuels, and changes in maintenance costs, it can be difficult to attach an exact life cycle cost to any system. While an exact value can be difficult to predict, life cycle cost can be expressed as a range or a distribution of potential costs. Many regions have historical data that can be compiled and used to predict future events; a data fitting algorithm can then be run to determine what the distribution of the costs would be (Emblemsvag, 2003). Previous studies have used Monte Carlo simulations as a means of evaluating the uncertainty of life cycle analysis (Pomponi et al., 2017; Hung, 2009), or attempted to introduce uncertain future parameters (Burhenne et al., 2013; Copiella et al., 2017;

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[3] The manuscript appearing as Chapter 7 of this thesis is intended to be submitted to the *Journal of Construction Engineering and Management (ASCE)*, at the time of publication of this thesis.

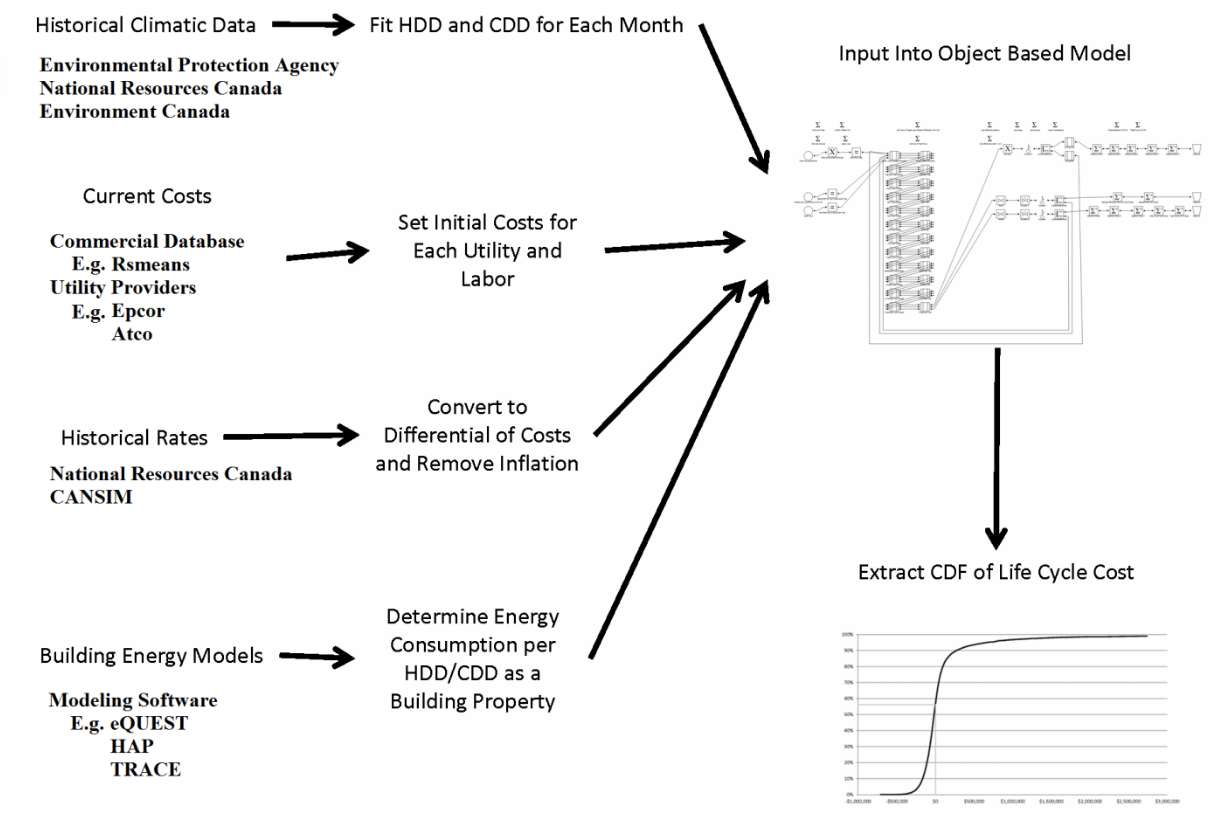


Figure 7.1: Through the compilation of currently available data, an object-based model can be used to compare multiple building systems' life cycle costs to allow designers to determine which system is preferable

Ewertowska et al., 2017). The proposed framework uses the generated distribution as a decision making tool rather than a means of evaluating uncertainty. As depicted in Figure 7.1, the result is a distribution of the outcome based on numerous variables. If multiple building systems are run in parallel, subjecting each system to the same weather and market fluctuations during each run of the simulation, then a direct comparison can be made between the systems and a cumulative distribution function of the ratio of advantage can be established based on the attribute under investigation. This allows decision makers to visualize the cost comparisons of each system and to establish the risks of choosing one system over another. Additionally, each system compared can be reviewed for the distribution of the output, allowing the estimation of volatility of costs for each system in the market and each location being analyzed.

7.2 Methodology

7.2.1 Simulation Design

The Simphony simulation environment was used as a basis for this model (although it should be noted that the model is independent of the software used to develop it) (AbouRizk et al., 2016). The internal tools provided in this simulation environment proved beneficial when producing distribution models for the economic and climatic variables considered in the simulation. The life cycle cost of a building is expressed as:

$$LCC = BC + \Sigma(MC+OC) + SC \qquad [7.1]$$

where

LCC = Life Cycle Cost ($)
BC = Building Cost ($)
MC = Maintenance Cost ($)
OC = Operating Costs ($)
SC = Salvage Costs ($)

The same criteria can be applied to individual systems within the building. Here the building cost becomes the cost of the individual building system, and operating and maintenance components become the maintenance and energy consumption of the individual building system being analyzed. As defined by Copiella et al. (2017), life cycle cost analysis is very sensitive to discount rates, which can substantially depress the value of future costs. While discount rates could be easily included in this simulation, they will not be included for the current analysis.

7.2.2 Energy Use:

The first task in analyzing any building system is to develop a model to simulate the energy use of the building based on the external climate and type of occupancy. A heating/cooling degree day method was used for the simulation described in the present study, given that the historical weather information is readily available, so the energy requirements to maintain the internal environment of the building was calculated on a per degree day basis. Other methods could be utilized to evaluate the energy uses of a building based on the local weather data that would be equally valid (White et al., 1996). Once rates of energy consumption for the building are identified, different systems can be evaluated based on the energy source fuel used, as well as the energy required for delivery per unit of energy. The energy source fuel can be expressed in terms of any energy form: gas, electricity, oil, etc. The quantity required per degree day for different types of energy can be evaluated using readily available energy modeling software. With the local costs per unit of energy easily obtainable, these values can be inputted in order to determine the starting cost.

7.2.3 Climatic Variation:

Most jurisdictions have historical weather data that can be used to produce a degree day distribution for both heating and cooling for a given month (Briggs, 1996), expressed as Heating

Degree Days (HDD) and Cooling Degree Days (CDD). These distributions can be used in the Monte Carlo simulation to determine the heating and cooling loads for a given building; because the systems under investigation are being run through the simulation in parallel, each system will be subject to the same weather variations. Since the heating and cooling distributions are asymmetrical, typically resulting in a Gamma or similar distribution, it should be noted that the average value is not necessarily representative of the conditions that will be seen in reality.

7.2.4 Cost Analysis:

Similar to climatic data, most regions will have historical economic data capturing local inflation, utility rates, labor costs, and other local economic information. Local governments in Canada have recorded this information and make it available for analysis (Government of Canada, 2016b), and other jurisdictions may make this information available as well. If this information is available and compiled and the monthly data compared (having been corrected for inflation), then a distribution of the derivatives of the economic factors can be generated. This can be applied not only to utility costs, but for labor costs in order to capture month-to-month maintenance cost fluctuations. Maintenance cost, it should be noted, has two components, the first being labor by staff, and the second being the salvage and replacement cost when components reach their end of life. Because the two are evaluated separately, labor cost can be tracked as the standard for routine maintenance, while the salvage and replacement cost can be used to represent the milestone events each system will undergo during its lifespan.

7.2.5 Tracking and Tabulating Results:

The simulation data is divided into two values: entity properties and global properties. The simulation is programmed as a set of progressive events through which data proceeds as depicted in Figure 7.2. Each system moves through the simulation as an entity and each entity also contains the "to date" cost and system properties with which it has been associated during its progression though the simulation. Here the global properties, it should be noted, are the current costs of fuel and labor. Each entity begins its trip though the simulation with the assigning of initial values to the entity properties. This includes estimates of the initial installation costs and the quantity of each fuel source required to service each degree day of heating or cooling. The initial costs can be fixed values (Hammond, 2006), or themselves can be distributions reflecting the uncertainty of working with predicted data (Acquaye, 2011) and the uncertainty in the availability of data.

While the efficiency of a system can decrease under partial load, it has been shown that a system can be modeled using a linear model to obtain the energy input required to deliver a specific unit of output energy (Butcher, 2011). This is achieved by assigning set standby fuel consumptions for each time period, then a fuel consumption per unit of required output for each system. The current value of salvage and replacement can also be assigned at this time if salvage and replacement of components is expected to occur during the simulated time period. As the entities move through the time periods of the simulation, which represent individual months in the annual cycle, the climatic loads for the specific time period are determined, and changes in costs are applied to the current global costs. If desired, inflation can be applied to all the global properties and expected future costs of each system, and discount rates can be applied as required. Once the climatic loads and costs for the specific month are set, the costs for that month can be applied to the total for each entity. The time period is tracked, such that any milestones, such as major component replacement, can be applied to each system as well.

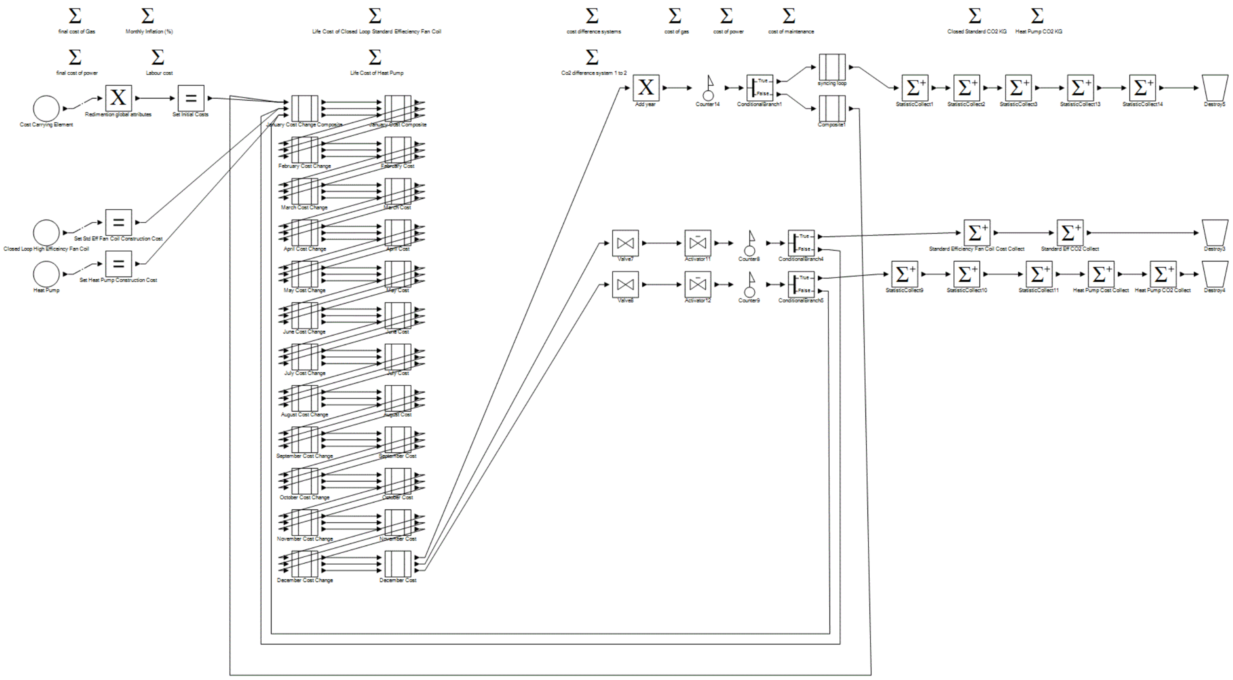


Figure 7.2: Graphical representation of object-based model in Simphony for illustration.

The simulation is set to operate for a number of annual cycles, with each month in the annual cycle representing an individual time period. With each iteration of the simulation, the total cost and emissions are determined for each system being considered, and, since the systems operate in parallel, all the conditions to which each system is subject during the run are identical. Using a Monte Carlo simulation, the distributions of possible life cycle costs for the various systems under investigation during the analyzed time period can be compared. The differences in each run can also be compared and tabulated, providing a direct comparison distribution. It is possible that there will be distribution overlap, with one system provided a superior final cost in only a certain portion of occurrences. It is possible that neither system would have a universal life cycle cost that is lower than the system it is being compared to, which appears to be a common misconception (ASTM International, 2017).

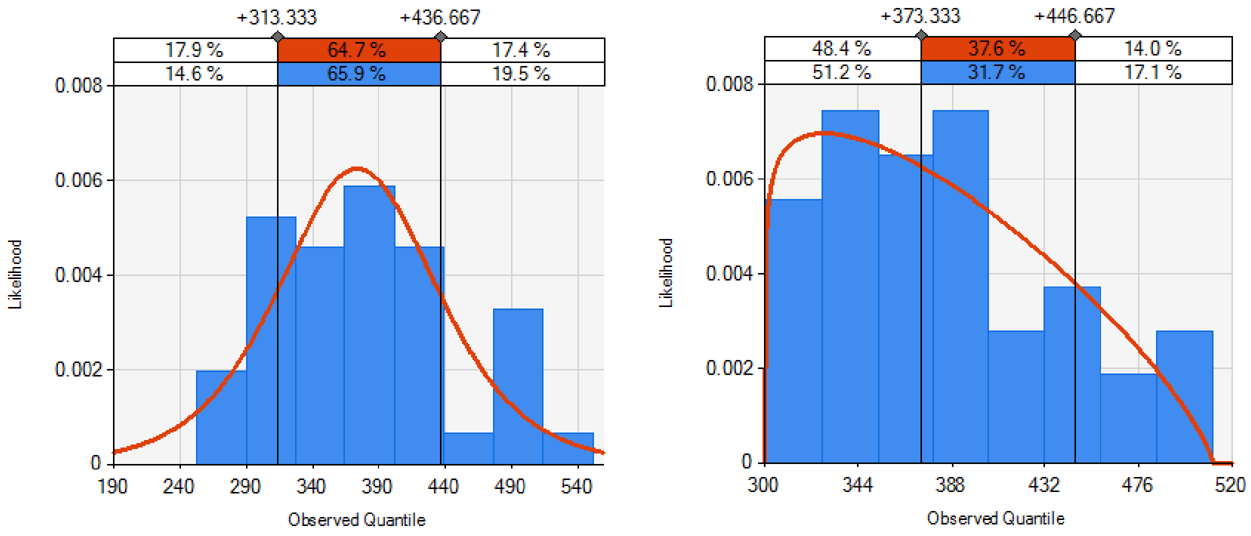
7.3Analysis

In order to analyze the functionality of the simulation, a pair of systems in a single location were compared for total cost. A rudimentary design for a specific building is established for each of the systems considered and a material list is generated. Given that the envelope and ventilation requirements are dependent on the building and not on the mechanical system installed, an efficiency analysis can be generated using the linear modeling technique mentioned earlier, which assigns a standby load and HDD load for each fuel type that the building uses. From this analysis, the quantity for each fuel is assigned on a per HDD/CDD basis.

As part of the analysis of the modeling technique, a 40-unit apartment in Edmonton, Alberta, Canada is used as the case building. Two systems are compared: a four-pipe fan coil system and a heat pump system.

The first step in the analysis is to tabulate the weather data for the location in question. Recorded weather data is available from the Government of Canada's "Environment and Natural Resources" service (Government of Canada. 2016b) in a spreadsheet format that can be analyzed to generate HDD and CDD distributions for each month. The majority of the weather data distributions result in a Gamma Distribution being selected for the individual months' HDD18 distributions, although a LogNormal distribution is found to be a better fit for a minority of the months. As the simulation model allows the distribution to be assigned for each month, the best fit is selected and inputted based on the suitability of the distribution and no specific distribution is favored. Selected distributions for the HDD18 (heating degree days below 18°C) are illustrated in Figure 7.3. Similar distributions are generated for CDD.

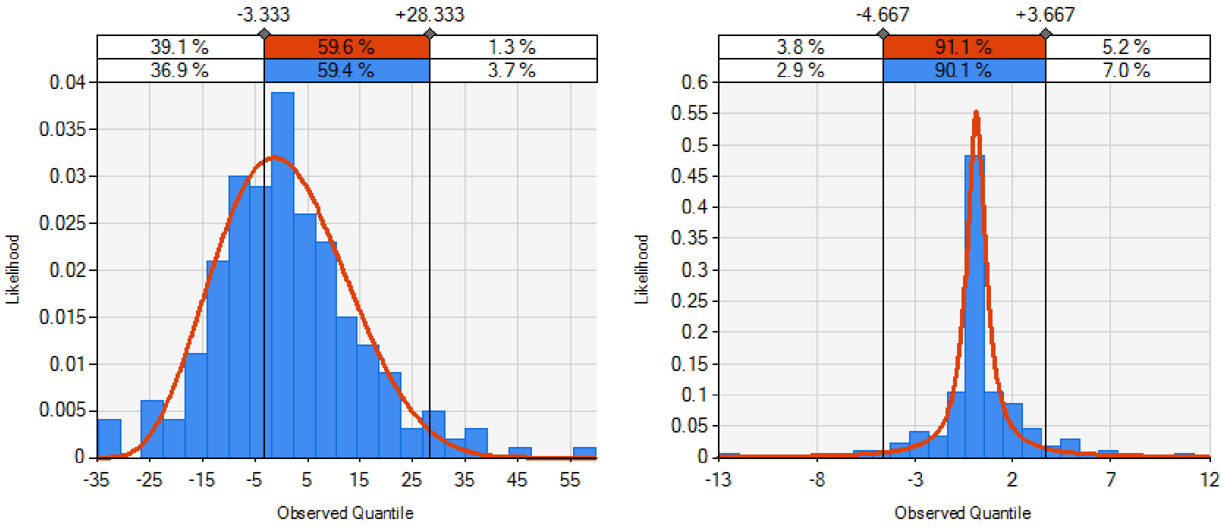
The next step is to determine the fluctuation in cost for fuel type and maintenance. The historical cost of fuel is available from the local Canadian government, as are the cost of labor and the local rate of inflation. Other jurisdictions would have to investigate if this information is available. If the rate of change in cost for each component is tabulated as a percent change over the time period being investigated and the rate of inflation is extrapolated accordingly, then a representative distribution for historical cost fluctuation can be generated. This is important as it characterizes the cost trends from month to month, and is more representative of actual costs than is a straight cost distribution.



April HDD 18

October HDD 18

Figure 7.3: April and October HDD18 fit results. April data was best fit using a Logistic distribution, while October was best fit using a Beta distribution. Similar distributions are fit for each month for both HDD and CDD.



% Change in Natural Gas Prices **% Change in Electricity Prices**

Figure 7.4: Monthly percent change in local natural gas and electricity prices excluding inflation.

The data sets can be converted to a distribution of rates of change for each of the cost inputs. The generated distributions for this analysis are included in Figure 7.4. During implementation of the analysis, the rate of inflation can be included in the monthly fluctuations to provide a total dollar cost for the simulation, or the inflation can be excluded in order to obtain a present value dollar cost. Different energy sources, it should be noted, have varying degrees of volatility based on the monthly change in price. While the local price of electricity in the case study was found to be relatively stable, the local price of natural gas historically had the potential to change rapidly, even on a monthly time scale. Such fluctuations have the potential to influence the comparisons, as different systems use different energy sources. Working with distributions of the rate of change as opposed to the historical costs, alternatively, results in a model cost that relates the costs of future months to the previous month, which is more realistic than using a cost distribution that does not reflect these trends. This also allows large confidence intervals to be represented in the price of fuel in order to capture future trends (Burhenne et al., 2013).

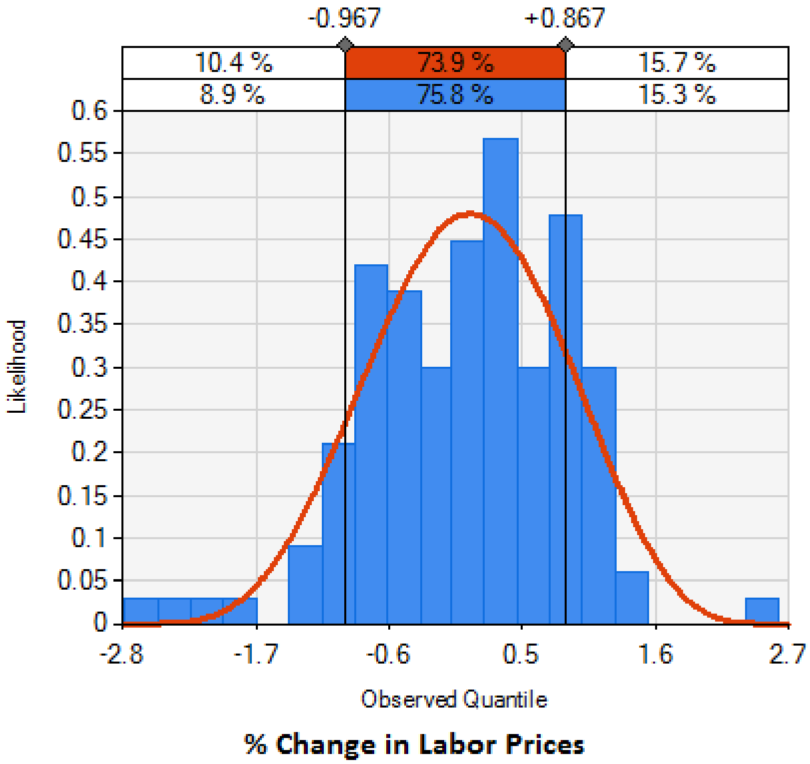


Figure 7.5: Monthly percent change in the price of local labor for maintenance activities excluding inflation.

The cost of maintenance is largely representative of labor costs, as both incidental and large-scale replacement of components are relatively infrequent compared to routine maintenance operations, which primarily involve labor costs. Estimates of the quantity of labor required for the installation or servicing of a component or system are available through a number of estimating databases, such as RSMeans, while the man-hour costs of labor can be extracted from local statistics. From this data, the monthly change in labor costs excluding inflation can be fit and inputted into the simulation. The local rate of change distribution from this case study is provided Figure 7.5. This is derived from data available through Statistics Canada (Government of Canada, 2016a).

The third step is to tabulate the parts lists for each of the designs and input the initial cost as the starting value for each system. The current market costs for fuel and maintenance are also inputted into the global properties as initial costs.

7.3.1 Test Case #1

Using the previously listed criteria, a 100,000 iteration sample run was conducted in order to compare two systems: System 1—a four-pipe fan coil with a standard-efficiency boiler (85% efficiency) and chiller system, and System 2—a heat pump with condensing boilers (95% efficiency) and a cooling tower. These systems were selected as they represent common heating and cooling systems, which are often compared for cost and efficiency. The output generated using this scenario is the Cumulative Distribution Function (CDF), shown in Figure 7.6. From the CDF, it can be determined that, for the conditions identified, there is a 55.3% probability that the four-pipe fan coil system will have a lower present value life cycle cost than will the heat pump system. It is important to note that, as they proceeded through the simulation in parallel, each system was subject to the exact same conditions and fluctuations during each iteration.

Further analysis of this test case identifies that the mean of the cost differences is $148,900 in favor of the heat pumps. Such a finding would provide the designer with valuable evidence that, while there is a greater probability that the fan coil system will have a lower life cycle cost over the heat pumps, there is also a risk that, if the fan coil were to become more expensive, it would be substantially more expensive. As a result, the decision tree analysis of the benefit as shown in Figure 7.7 would suggest that the heat pump design is preferable (Moore et al., 2001).

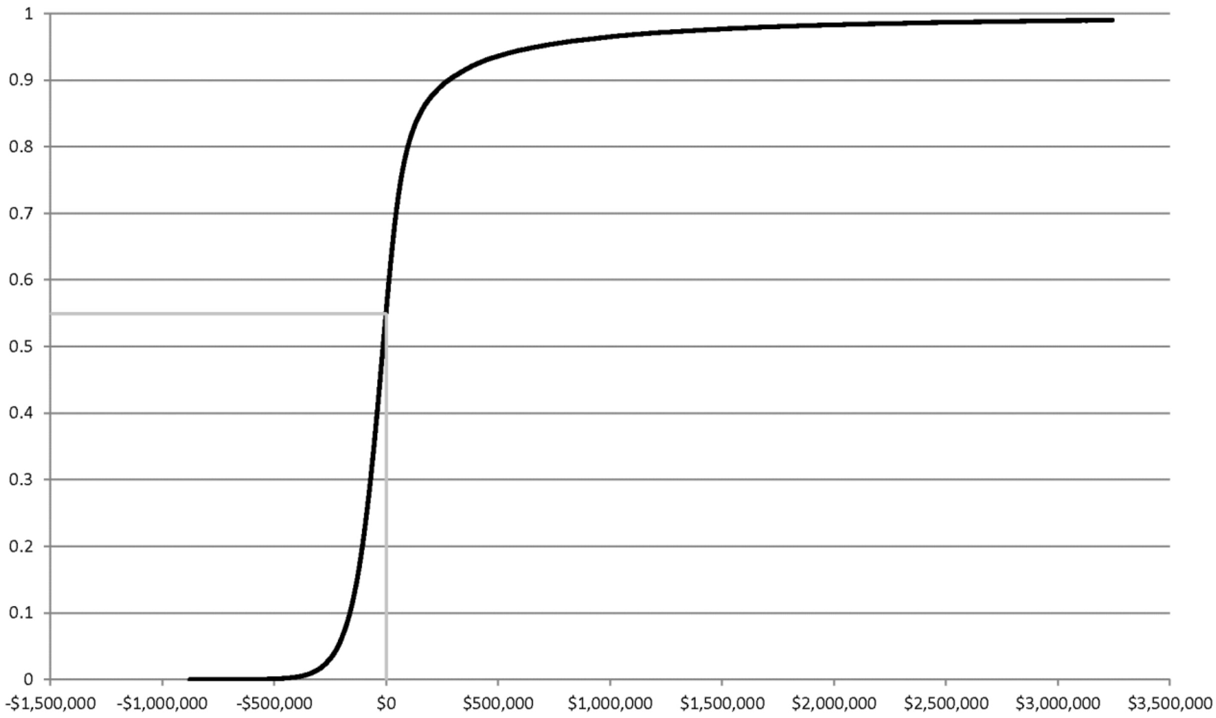


Figure 7.6: CDF of life cycle cost in Canadian Dollars of a four-pipe fan coil system with 85% efficiency boiler minus life cycle cost of a heat pump system with 95% efficiency boiler

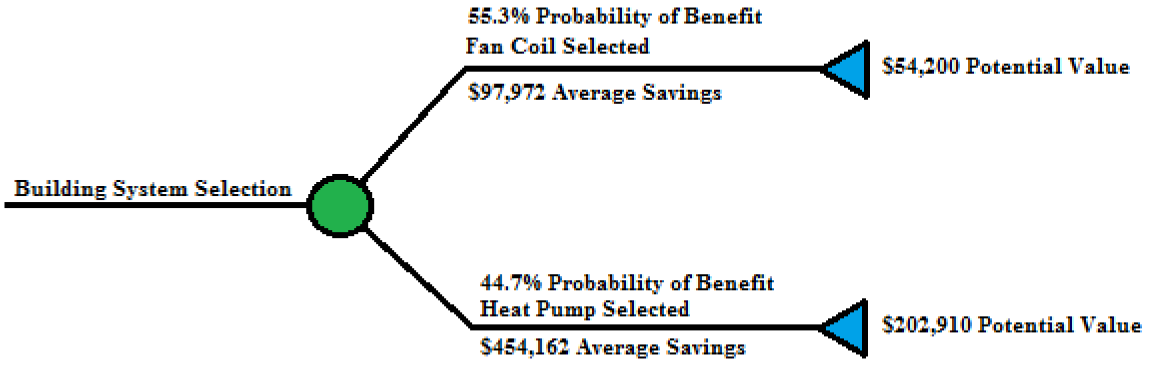


Figure 7.7: Decision tree analysis of the cost benefit in Canadian Dollars of a four-pipe fan coil system with 85% efficiency boiler minus life cycle cost of a heat pump system with 95% efficiency boiler

7.3.2 Test Case #2

To evaluate whether or not it is possible to improve the fan coil system, another test case was run. This test case compared the same heat pump system used previously to a high-efficiency fan coil system. The fan coil systems compared were fundamentally the same, each furnished with a four-pipe fan coil with boilers and a chiller, only now a lower heating water temperature was used to permit the installation of condensing, high-efficiency boilers, similar to the equipment considered for the heat pump system. A 100,000-iteration sample run was conducted, with the results depicted in Figure 7.8.

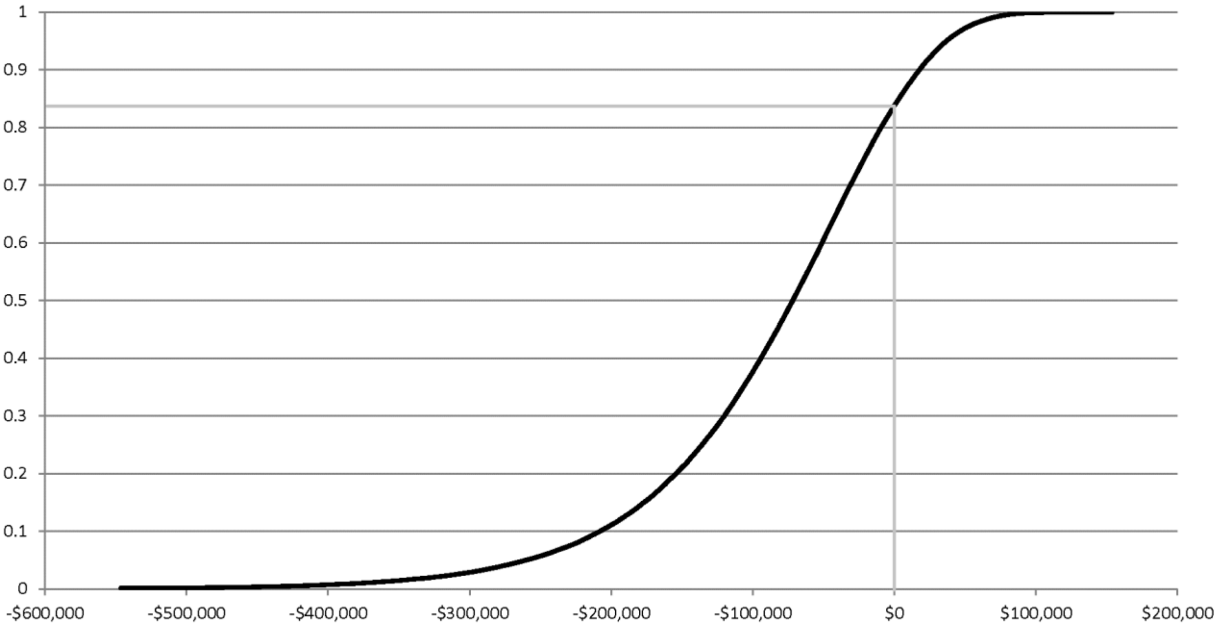


Figure 7.8: CDF of life cycle cost in Canadian Dollars of a four-pipe fan coil system with 95% efficiency boiler minus life cycle cost of a heat pump system with 95% efficiency boiler

This scenario identified that there was an 83.8% probability that the high-efficiency fan coil system would have a lower life cycle cost to the heat pump system. Additionally, the mean of the cost difference was found to be $86,400 in favor of the fan coil. From the analysis, both the probability and decision tree analysis shown in Figure 7.9 would favor the installation of a high-efficiency fan coil system in the case region's current economic environment when compared to a central heat pump.

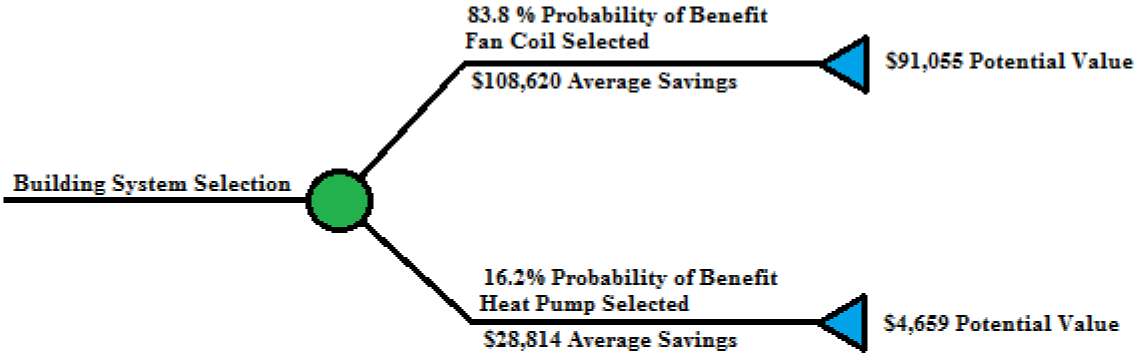


Figure 7.9: Decision tree analysis of the cost benefit in Canadian Dollars of a four-pipe fan coil system with 95% efficiency boiler minus life cycle cost of a heat pump system with 95% efficiency boiler

7.4 Conclusions

Through the use of an object-based simulation system, it is possible to compare the life cycle costs of different building mechanical systems prior to the final design and construction of the building, while factoring in volatility of operating costs. Through the use of a Monte Carlo simulation, historical changes in utility and maintenance costs, and local climatic data, multiple systems can be compared in terms of life cycle costs. This technique provides a direct comparison of each system using identical conditions with each iteration, and uses a more accurate differential of costs with each time period analysis than would a simple distribution of historical costs. Furthermore, due to the ease of use of the object-based simulation package, a large number of variables can be included in the simulation. Based on the capacity of the computational tools currently available in the market, reasonable simulation completion times can be expected, thereby allowing for simulations containing large numbers of iterations to be performed to offset the variation that can be generated by including a large number of variables.

It is imperative that the output of the Monte Carlo CDF generated in the simulation be carefully analyzed. While the probability ty may indicate that one system would be preferable over another, the range of results could produce a decision tree analysis that is contrary to the probability analysis. This scenario was observed in Test Case 1, where the standard-efficiency fan coil was found to have a better probability to have a superior life cycle cost over the heat pump system, while the volatility in the price of certain utilities resulted in a decision tree analysis in which the lower probability heat pump system was deemed to be preferable.

CHAPTER 8: CONCLUSIONS

8.1 Research Summary

The promotion and use of potable water as a hydronic medium in multi-unit residential buildings has been a topic of interest for many years. Originally intended as a construction cost- and energy-saving technique for use in single-family dwellings, the concept underlying this strategy has been adapted for use in larger buildings. While building systems that utilize potable water as a hydronic medium have been in use for many years, a substantial investigation into the performance of these systems or the impacts they have on the occupants of the building has yet to be conducted. Additionally, the claims of construction and operational cost savings due to the use of potable water as a hydronic medium when compared to conventional hydronic systems had not been substantiated. This research thus aims to address these shortfalls through direct investigation of system performance, occupant perceptions, and the development of a novel life cycle analysis technique to explore costs.

First, the performance of systems that utilize potable water as a hydronic medium is addressed as compared to conventional systems, which keep service water and hydronic water separate. This comparison establishes that in terms of heating, systems which utilize potable water as a hydronic medium perform substantially similarly to systems where service water and hydronic water are piped separately. Heating performances fit well to a linear model which expresses building efficiency as steady state efficiency with a standby loss. This comparison, however, is not consistent when cooling is compared. Under cooling conditions the performance of systems which utilize potable water as a hydronic medium is inconsistent and does not fit well to the proposed modeling techniques applied to the heating performance.

Investigating the effects of utilizing potable water as a hydronic medium on the occupant perceptions of the water identifies that under normal operating procedures, concerns that the building occupants would have a reduced perception of their service water quality are minimal. If the occupants of the building are consuming the same volume of service water as the volume of the system, then any changes to the palatability of the water in the system will be below the perception level of the occupants. The volume of the system would need to be two or more times the volume of water consumed by the occupants each day for there to be a noticeable effect on how the occupants perceive the water when compared to metered utility water that has not been used for HVAC purposes. As most buildings have system volumes that are quite low when compared to the volume the occupants are consuming each day, a substantial improvement in water-use efficiency would be required before there would be any concern that using the potable service water for hydronic purposes would have a negative impact on occupant perceptions.

Investigation of the costs of using potable water as a hydronic medium when compared to other systems identifies serious flaws with the method by which life cycle analysis is conducted. The current procedure for life cycle analysis involves the use of set costs for utility rates, and the average climatic data to estimate the operational costs of a system over time. The problem with this procedure is that it fails to fully account for the volatility of commodity prices and labour rates. Additionally, it does not factor in the variation in weather that can be experienced in any individual month. In previous studies, iterative and Monte Carlo style simulations were used to evaluate the sensitivity of the final result to an individual input. However, the present research proposes that the iterative simulation process not be used to evaluate sensitivity, but to provide a CDF as the final result. Given that the decision is a matter of System A versus System B, the CDF provides the probability of preferability for either system and the average value in the case of the lower-cost system. From this, a decision tree analysis is conducted to determine which system is more desirable.

8.2 Research Contribution

The contributions of the research are as follows:

1. It has been shown that the energy use as a result of utilizing potable water as a hydronic medium can be illustrated utilizing a linear model with a steady state efficiency and a standby loss for the complete building system.
2. The performance of systems that utilize potable water as a hydronic heating medium is similar to the performance of systems which operate as a closed system for heating.
3. Cooling systems which utilize potable water as a hydronic medium must be aware that inlet service water temperatures that are above the desired cooling water temperatures will result in inefficiencies if cooling the cold service water for occupant use is not intended.
4. This research confirms that utilizing potable water as a hydronic medium in systems which have a system volume that is less that the occupant daily consumption will cause no change in occupant perceptions of the service water they are receiving.
5. This research identifies a relationship between the daily consumption rate of water by the system occupants, the volume of the hydronic system, and changes in occupant perception of the quality of the service water. This is useful for evaluating the impact of high-efficiency water fixtures, and the potential effects of implementing this distribution strategy in low-water-use buildings, such as commercial buildings.

6. Using life cycle analysis, a new framework for deciding between various building systems is proposed that accounts for volatility in market costs and weather as opposed to only measuring for sensitivity of the final result to these characteristics. This framework has the potential to result in different decisions compared to conventional techniques, which use set values.

8.3 Future Research

Future research into utilizing potable water as a hydronic medium include investigating possible techniques for integrating with high-efficiency systems and investigating the limitation of building materials. Some of these avenues of research are as follows:

1. Investigate the effects of integrating the use of potable water as a hydronic medium for systems that utilize alternate high-efficiency energy sources such as air source systems for large buildings.
2. Develop hybrid distributions that integrate potable water hydronic distributions with other systems, such as variable refrigerant flow systems, as a means of addressing large systems where occupant consumption may be low.
3. Investigate piping materials and longevity of systems that utilize potable water as a hydronic medium. While potable water systems do not require chemical treatment for operation, materials and components which are compatible with potable water are limited.
4. Investigate further how discount factors can impact the influence of cost volatility with regards to making system decisions based on Life Cycle Analysis.

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APPENDIX A: Test Apparatus and Equipment Cut Sheets

Included in this appendix are the cut sheets for the major components of the system, including hot water tank, pumps, fan coils, heat exchanger, and chiller.

BTH-120
through
BTH-500

UP TO 96% THERMAL EFFICIENCY, DIRECT VENT

FEATURES

The A. O. Smith Cyclone Xi family of products represents the industry's most technologically advanced commercial water heaters. The innovative Cyclone Xi design takes performance to its highest level with efficiencies of 95% and 96%. Models are available from 120,000 BTUs up to 500,000 BTUs. In addition, the Cyclone Xi features an Intelligent Control system making it the smartest water heater in the industry. All models are ENERGY STAR® Qualified.

Cyclone Xi provides outstanding hot water output, with dramatic savings on operating costs compared to units with standard 80% efficiency. A. O. Smith's leading-edge engineering delivers conventional power-vent or power direct-vent versatility, low NOx emissions and excellent space-saving characteristics. Powered anodes, standard on all Cyclone Xi models, provide superior tank protection for years of trouble free operation.

INTELLIGENT CONTROL SYSTEM WITH LCD DISPLAY

- Exclusive A. O. Smith designed control system
- Provides detailed water heater status information
- Precise temperature control
- Built-in diagnostics
- Run history information
- Cyclone water heaters are iCOMM™ compatible and can be monitored from remote locations. Call 1.888.WATER02 for more information.

SUBMERGED COMBUSTION CHAMBER, WITH HELICAL HEAT EXCHANGER COIL

- Positioned in center of tank, surrounded by water to virtually eliminate radiant heat loss from chamber
- Spiral heat exchanger keeps hot burner gases swirling, uses centrifugal force to maximize efficiency of heat transfer to water in tank
- Spiral shaped heat exchanger reduces the accumulation of lime scale; maintains higher efficiency performance over time.

POWERED ANODES STANDARD ON ALL MODELS

- Provides long-lasting tank protection in varying water conditions
- Anodes are of a permanent design and do not require replacement unless damaged

PERMAGLAS® ULTRA COAT™GLASSLINING

- Exclusive process provides superior protection against corrosion
- Both sides of heat exchanger coil are lined for protection against flue gas condensate inside coil

MECHANICAL VENTING VERSATILITY

- Conventional power-venting or power-direct venting
- Vents vertically or through sidewall
- Direct-vent intake and exhaust pipe can terminate separately outside building, or through single opening, using concentric vent assembly
- Uses inexpensive PVC, CPVC or ABS pipe for intake and exhaust. Canadian installations require ULC S636 listed PVC or CPVC pipe for intake and exhaust.

HIGH EFFICIENCY PRE-MIX POWERED BURNER

- Down-fired pre-mix burner provides optimum efficiency and quiet operation
- Top-mounted radial burner design ensures optimum combustion efficiency

Revised June 2013

OTHER CYCLONE Xi FEATURES

SPACE-SAVING DESIGN FOR INSTALLATION FLEXIBILITY

- Reduced footprint, ease of service, protection from water damage in case of flooding
- Easy to remove top cover for convenient access to serviceable parts
- 0˝ installation clearances on sides and rear, 4˝ installation clearance in front for Handhole Cleanout of unit and 1" installation clearance on top, however more room on top makes model easier to service.
- Handhole cleanout allows easy access to tank interior for cleaning
- 0˝ clearance to combustibles, approved for installation on combustible floors

CODES AND STANDARDS

- CSA certified and ASME rated T&P relief valve
- Maximum hydrostatic working pressure: 160 PSI
- BTH-120-250 Models are design-certified by CSA International, according to ANSI Z21.10.3 - CSA 4.3 Standards governing storage-type water heaters.
- BTH-300-500 Models are design-certified by Underwriter's Laboratories (UL), Inc., according to ANSI Z21.10.3 - CSA 4.3 standards governing storage-type water heaters.
- Meets or exceeds the thermal efficiency and standby loss reqiurements of the U.S. Department of Energy and current edition ASHRAE/IESNA 90.1
- Design-certified by Underwriter's Laboratories (UL), Inc. to NSF standard 5
- Complies with SCAQMD Rule 1146.2 and other Air Quality Management Districts with similar requirements for low NOx emissions
- ASME tank construction optional on all models.

THREE-YEAR LIMITED TANK WARRANTY

- For complete warranty details, consult written warranty shipped with heater, or contact A. O. Smith (5-year extended warranty is optional).

INSTALLATION CONSIDERATIONS

1. Condensate Drain – This is a fully condensing water heater and should be located near a drain to permit proper disposal of condensate.

2. Vent Termination – Exhaust gases of this water heater are less than 140°F. In cold climates water vapor in flue gases will condense into a cloud of vapor where the vent exits the building. This vapor can gradually discolor exterior building surfaces. Vent termination should be located where this vapor cloud and potential discoloration are not a concern. Extending the vent termination up to 6˝ from the wall helps vapor from being trapped along a building's face. To avoid this problem, the vent can be terminated on the roof. Always locate vent termination above the maximum snowline, and do not locate vent termination above a walkway.

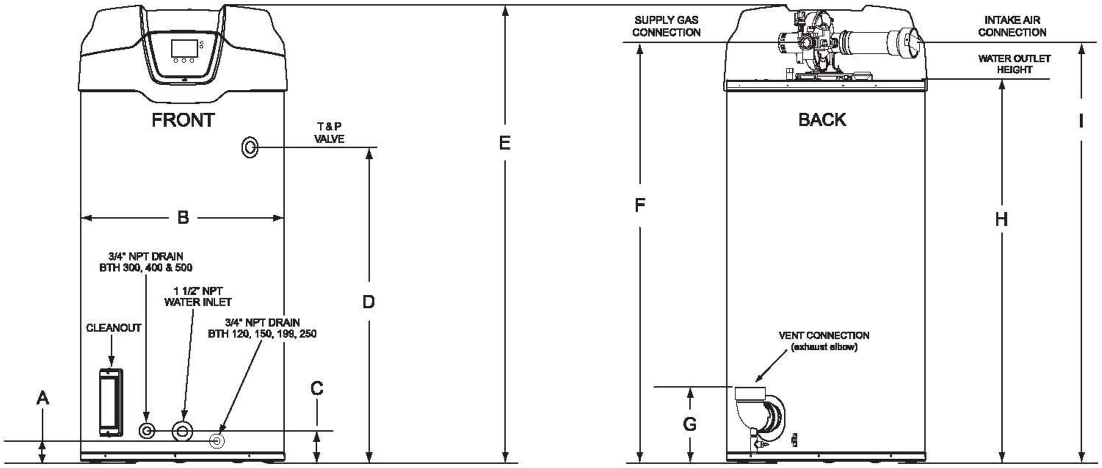
3. Air Intake – In cold climates, air intake should be located at least four feet from the vent termination of the water heater and any other appliance vents that discharge moisture-laden air (such as clothes dryers). This will help prevent freeze-over of the intake screen required to prevent foreign objects from entering the intake pipe. Air intake should be located above the maximum snowline.

4. Blockage Sensors – The water heater is equipped with sensors to shut it down if blockage of vent or air intake occurs. The water heater control system will display detailed diagnostic information on the LCD screen to help service technicians quickly locate and correct the problem.

5. Noise – Vent terminal should be located away from bedroom windows or other areas where blower noise will be objectionable. Avoid venting into corners or confined areas, which will amplify sound. Anchoring intake or vent pipe to walls or ceilings can cause noise to be transmitted to living areas, and isolation mounts should be used where anchoring is required.

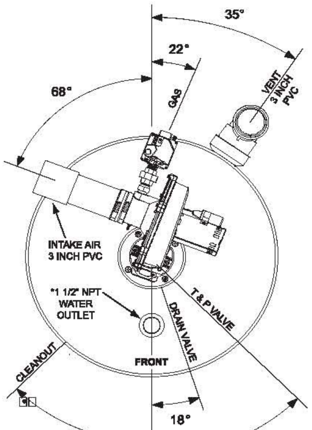
6. Optional Concentric Vent Kit - Helps to minimize unsightly wall/roof penetrations.
   BTH-120 - 300 vent kit p/n 9006328005
   BTH-400 - 500 vent kit p/n 9006144005

Commercial Gas Water Heaters

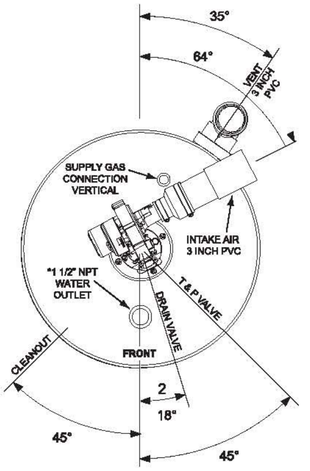


MODEL	DIMENSIONS									SHIP WEIGHT STD	SHIP WEIGHT ASME
	A	B	C	D	E	F	G	H	I		
	INCHES/CM	INCHES/CM	INCHES/CM	INCHES/CM	INCHES/CM	INCHES/CM	INCHES/CM	INCHES/CM	INCHES/CM	LBS/KG	LBS/KG
BTH 120(A)	3/7.62	27.75/70.5	6.3/16	35/88.9	55.5/141	48/121.9	11/27.9	42/106.7	47.5/120.6	460/208	490/222
BTH 150(A)	3/7.62	27.75/70.5	6.3/16	55.5/141	75.5/191.8	68.5/174	11/27.9	63/160	69/175.3	555/252	595/270
BTH 199(A), 250(A)	3/7.62	27.75/70.5	6.3/16	55.5/141	75.5/191.8	75.5/191.8	11/27.9	63/160	69/175.3	555/252	595/270
BTH 300(A), 400(A), 500(A)	N/A	33.12/84.1	4.86/12.34	50.77/129	75.5/191.8	69/175.3	12/30.5	63/160	69/175.3	855/408	855/408

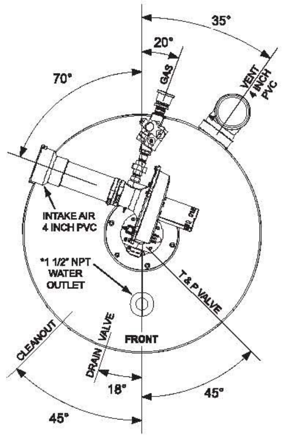
BTH 120 & 150



BTH 199 & 250



BTH 300, 400 & 500



* Center line of water outlet on top of the water heaters is approximately 7 inches from the front edge of the water heater

For Technical Information and Automated Fax Service, call 800-527-1953. A. O. Smith Corporation reserves the right to make product changes or improvements without prior notice.

Commercial Gas Water Heaters

MAXIMUM EQUIVALENT VENT LENGTHS BTH 120 - 250

*Number of 90° Elbows Installed	3 Inch Pipe	4 Inch Pipe
	Maximum Feet (Meters)	Maximum Feet (Meters)
One (1)	45 feet (13.7 meters)	115 feet (35.0 meters)
Two (2)	40 feet (12.2 meters)	110 feet (33.5 meters)
Three (3)	35 feet (10.7 meters)	105 feet (32.0 meters)
Four (4)	30 feet (9.1 meters)	100 feet (30.5 meters)
Five (5)	----	95 feet (29.0 meters)
Six (6)	----	90 feet (27.4 meters)

* Maximum number of 90° elbows allowed for the vent (exhaust) pipe is four (4) when installing 3 inch pipe and six (6) when installing 4 inch pipe. Maximum number of 90° elbows allowed for intake air pipe is four (4) when installing 3 inch pipe and six (6) when installing 4 inch pipe. Two (2) 45° elbows equal one (1) 90° elbow.

MAXIMUM EQUIVALENT VENT LENGTHS BTH 300 - 500

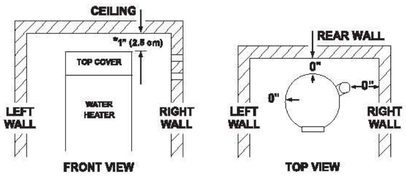
*Number of 90° Elbows Installed	4 Inch Pipe	6 Inch Pipe
	Maximum Feet (Meters)	Maximum Feet (Meters)
One (1)	65 feet (19.8 meters)	115 feet (35.0 meters)
Two (2)	60 feet (18.2 meters)	110 feet (33.5 meters)
Three (3)	55 feet (16.8 meters)	105 feet (32.0 meters)
Four (4)	50 feet (15.2 meters)	100 feet (30.5 meters)
Five (5)	45 feet (13.7 meters)	95 feet (29.0 meters)
Six (6)	40 feet (12.2 meters)	90 feet (27.4 meters)

* Maximum number of 90° elbows allowed for the vent (exhaust) pipe is six (6). Maximum number of 90° elbows allowed on the intake air pipe is six (6). Two (2) 45° elbows equal one (1) 90° elbow.

MINIMUM SUPPLY GAS LINE SIZE

MODEL	NATURAL GAS	PROPANE GAS
BTH 120(A)	1/2" NPT	1/2" NPT
BTH 150(A)	3/4" NPT	3/4" NPT
BTH 199(A)	3/4" NPT	3/4" NPT
BTH 250(A)	3/4" NPT	3/4" NPT
BTH 300(A)	1 1/4" NPT	1 1/4" NPT
BTH 400(A)	1 1/4" NPT	1 1/4" NPT
BTH 500(A)	1 1/2" NPT	1 1/4" NPT

INSTALLATION CLEARANCES



*Minimum clearance to remove top cover

INPUT/EFFICIENCIES

MODEL	TYPE OF GAS	INPUT		Thermal Efficiency	ASME	Non-ASME
		BTUH	KW			
BTH 120(A)	NATURAL/ PROPANE	120,000	35	95%	60 U.S. Gal/ 227 Litres	60 U.S. Gal/ 227 Litres
BTH 150 (A)	NATURAL/ PROPANE	150,000	44	95%	100 U.S. Gal/ 379 Litres	100 U.S. Gal/ 379 Litres
BTH 199 (A)	NATURAL/ PROPANE	199,900	58	95%	100 U.S. Gal/ 379 Litres	100 U.S. Gal/ 379 Litres
BTH 250 (A)	NATURAL/ PROPANE	250,000	73	95%	100 U.S. Gal/ 379 Litres	100 U.S. Gal/ 379 Litres
BTH 300 (A)	NATURAL/ PROPANE	300,000	88	96%	130 U.S. Gal/ 497 Litres	119 U.S. Gal/ 450 Litres
BTH 400 (A)	NATURAL/ PROPANE	399,900	117	95%	130 U.S. Gal/ 497 Litres	119 U.S. Gal/ 450 Litres
BTH 500 (A)	NATURAL/ PROPANE	499,900	146	95%	130 U.S. Gal/ 497 Litres	119 U.S. Gal/ 450 Litres

Recovery capacities are based on heater performance at 95% and 96% thermal efficiency.
Add "A" to model number when ordering ASME.
Maximum gas supply pressure for 120-250: 10.5" W.C. natural gas 14" W.C. propane. Maximum gas supply pressure for 300-500 10.0" W.C. natural gas 12.0" W.C. propane. Electrical requirements: 120 VAC/60Hz, Blower 2.2 Amps FL, Igniter 4.0 Amps.

For Technical Information and Automated Fax Service, call 800-527-1953. A. O. Smith Corporation reserves the right to make product changes or improvements without prior notice.

MODEL	U.S. Gallons/Hr and Litres/HR at TEMPERATURE RISE INDICATED											
	F°	30F°	40F°	50F°	60F°	70F°	80F°	90F°	100F°	110F°	120F°	130F°	140F°
	C°	17C°	22C°	28C°	33C°	39C°	44C°	50C°	56C°	61C°	67C°	72C°	78C°
BTH 120(A)	GPH	461	345	276	230	197	173	154	138	126	115	106	99
	LPH	1744	1308	1046	872	747	654	581	523	476	436	402	374
BTH 150 (A)	GPH	576	432	345	288	247	216	192	173	157	144	133	123
	LPH	2179	1635	1308	1090	934	817	726	654	594	545	503	467
BTH 199 (A)	GPH	767	575	460	384	329	288	256	230	209	192	177	164
	LPH	2904	2178	1743	1452	1245	1089	968	871	792	726	670	622
BTH 250 (A)	GPH	960	720	576	480	411	360	320	288	262	240	221	206
	LPH	3632	2724	2179	1816	1557	1362	1211	1090	991	908	838	778
BTH 300 (A)	GPH	1164	873	699	582	499	436	388	349	318	291	269	250
	LPH	4406	3304	2644	2203	1888	1652	1469	1322	1201	1102	1017	945
BTH 400 (A)	GPH	1552	1164	931	776	665	582	517	466	423	388	359	332
	LPH	5875	4406	3525	2938	2518	2203	1958	1763	1602	1469	1356	1259
BTH 500 (A)	GPH	1919	1439	1151	959	822	720	640	576	523	480	443	411
	LPH	7263	5447	4358	3631	3113	2724	2421	2179	1981	1816	1676	1556

SUGGESTED SPECIFICATION

(Natural or Propane) gas water heater(s) shall be A. O. Smith Cyclone XI model # _________ or equal, with up to 96% thermal efficiency, a storage capacity of ______ gallons, an input rating of __________ BTUs per hour, a recovery rating of ___________ gallons per hour (gph) at 100°F rise and a maximum hydrostatic working pressure of 160 PSI. Water heater(s) shall: 1. Have seamless glasslined steel tank construction, with glass lining applied to all water-side surfaces after the tank has been assembled and welded; 2. Meet the thermal efficiency and standby loss requirements of the U. S. Department of Energy and current edition of ASHRAE/ IESNA 90.1 3. Have foam insulation and a CSA Certified and ASME rated T&P relief valve; 4. Have a down-fired power burner designed for precise mixing of air and gas for optimum efficiency, requiring no special calibration on start-up; 5. Be approved for 0˝ clearance to combustibles.

Heater shall be supplied with maintenance-free powered anode.

The control shall be an integrated solid-state temperature and ignition control device with integral diagnostics, graphic user interface, fault history display, and shall have digital temperature readout.

1. The BTH-120-250 models are design-certified by CSA International, according to ANSI Z21.10.3 - CSA 4.3 standards governing storage-type water heaters. The BTH-300-500 models are design-certified by Underwriter's Laboratories (UL), Inc., according to ANSI Z21.10.3 - CSA 4.3 standards governing storage type water heaters; 2. Meet the thermal efficiency and standby loss requirements of the U. S. Department of Energy and current edition ASHRAE/IESNA 90.1. Complies with SCAQMD Rule 1146.2 and other air quality management districts with similar requirements for low NOx emissions.

120K-250K BTU Input:

For Standard Power Venting: Water heater(s) shall be suitable for standard power venting using a (3" or 4") ____ diameter PVC pipe for a total distance of (50ft. or 120 ft.) ____ equivalent feet of vent piping.

For Power Direct Venting: Water heater(s) shall be suitable for power direct venting using a (3" or 4") ____ diameter PVC pipe for a total distance of (50ft. or 120 ft.) ____ equivalent feet of vent piping and (50ft. or 120 ft.) ____ equivalent feet of intake air piping.

300K - 500K BTU Input:

For Standard Power Venting: Water heater(s) shall be suitable for standard power venting using a (4" or 6") ____ diameter PVC pipe for a total distance of (70ft. or 120 ft.) ____ equivalent feet of vent piping.

For Power Direct Venting: Water heater(s) shall be suitable for power direct venting using a (4" or 6") ____ diameter PVC pipe for a total distance of (70ft. or 120 ft.) ____ equivalent feet of vent piping and (70ft. or 120 ft.) ____ equivalent feet of intake air piping.

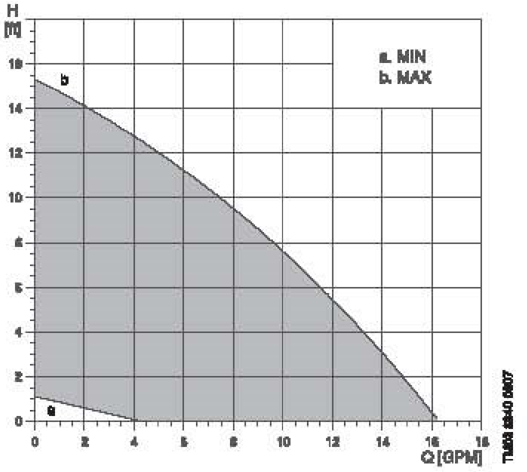
Operation of the water heater(s) in a closed system where thermal expansion has not been compensated for (with a properly sized thermal expansion tank) will void the warranty.

Water heater should incorporate the iCOMM™ system for remote monitoring, leak detection and fault alert.

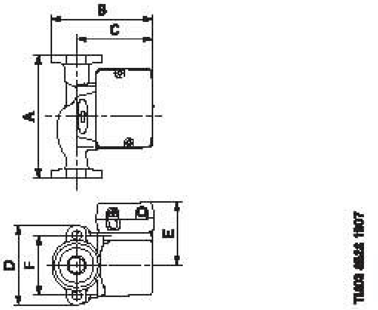
Technical data

UP 15-42 F/VS

UP 15 Variable Speed



UP 15-42 F/VS



Flow range:	0-16 gpm
Head range:	0-15.5 feet
Motors:	2-pole, single-phase
Max. liquid temperature:	205 °F (96 °C)
Min. liquid temperature:	36 °F (2 °C)
Max. system pressure:	145 psi (10 bar)

Model	Volts	Amps	Watts	Hp	Capacitor
UP 15-42 F/FV	115	0.74	85	1/25	10µF/180 V

Approvals

C UL US LISTED

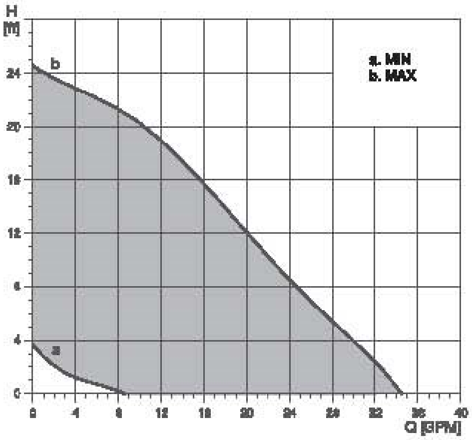
Variable speed models include the following features:

- Three speed control options:
  1) Manual
  2) Voltage: 0-10V(DC) or 2-10V(DC)
  3) Current: 0-20mA or 4-20 mA
- Dip switch control selection
- Pump exercising
- Manual offset dial
- Performance indicator LED's.

Model type	Product number	Dimensions [inches]						Connection type and size	Shipping weight [lbs]
		A	B	C	D	E	F		
UP 15-42 F/VS	59896807	6 1/2	6 1/4	4	4 3/16	3 1/4	3 5/32	GF 15/26 flange (2) 1/2" dia. bolt holes	7 1/2

Note: Dimensions in inches unless otherwise noted.

UP 26 Variable Speed



Flow range:	0-34 gpm
Head range:	0-24.5 feet
Motors:	2-pole, single-phase
Max. liquid temperature:	195 °F (91 °C)
Min. liquid temperature:	36 °F (2 °C)
Max. system pressure:	145 psi (10 bar)

Model	Volts	Amps	Watts	Hp	Capacitor
UP 26-64 F/VS	115	1.7	185	1/12	5µF/180 V

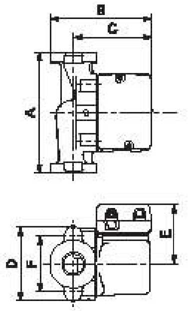
Approvals

c UL US LISTED

Variable speed models include the following features:

- Three speed control options:
  1) Manual
  2) Voltage: 0-10V(DC) or 2-10V(DC)
  3) Current: 0-20mA or 4-20 mA
- Dip switch control selection
- Pump exercising
- Manual offset dial
- Performance indicator LED's.

UP 26-64 F/VS



Model type	Product number	Dimensions [inches]						Connection type and size	Shipping weight [lbs]
		A	B	C	D	E	F		
UP 26-64 F/VS	52722553	6 1/2	6 3/8	5 1/16	4 1/8	3 1/2	3 5/32	GF 15/26 flange (2) 1/2" dia. bolt holes	11 1/4

Note: Dimensions in inches unless otherwise noted.

DRAWING TRANSMITTAL SHEET

JOB NO. E24655

DATE September 26, 2013

☑ **EDMONTON SALES OFFICE** 4266-91A STREET EDMONTON AB T6E 5V2 (780) 462-4101	**CANADIAN HEAD OFFICE** CALGARY AB	**CANADIAN FACTORY** CALGARY AB EDMONTON AB NEWMARKET ON	**OTHER CANADIAN SALES OFFICES** VANCOUVER, CALGARY, SASKATOON, REGINA, WINNIPEG, LONDON, SUDBURY, TORONTO, HAMILTON, OTTAWA, MONTREAL, HALIFAX, MONCTON

CONTRACTOR ENGINEERED AIR SALES (EDM)

ADDRESS 4266 91A STREET
EDMONTON AB
T6E 5V2

ENGINEER ROBERT PRYBYSH

JOB NAME U OF A OPEN LOOP RESEARCH

☐ THIS ORDER IS SUBJECT TO APPROVAL. MANUFACTURING IS HELD PENDING RETURN OF ONE APPROVED COPY OF THESE FORMS TO THE INDICATED OFFICE.

☑ THIS ORDER IS NOT SUBJECT TO APPROVAL AND IS BEING MANUFACTURED ACCORDING TO THE ATTACHED FORMS.

COPIES ENCLOSED	DESCRIPTION
2	Eng A Submittal Record
2	Eng A Mechanical Drawing
2	Eng A Internal Wiring Diagram
2	Eng A Electrical Data Sheet
2	Eng A Installation Operation and Maintenance Manual

PER PERRY ZAPERNICK / YN

SUBMITTAL RECORD

JOB NAME: U OF A OPEN LOOP RESEARCH **JOB NO:** E24655(E24655)
CUSTOMER: ENGINEERED AIR SALES (EDM) **ENGINEER:** ROBERT PRYBYSH
EngA MODEL: HFC-6\C **QTY:** 6 **TAG:** FC-1 to FC-6

SHIPPING AND APPROVAL INFORMATION

MOUNTING Indoor Ceiling Hung **ACCESS** As Per Drawing
NO. OF PIECES 1 Unit **SHIPPING WEIGHT** 89 lb (40 kg)

- CSA approval.
- Unit operates at the altitude of 0-4500 ft(0-1372 m).

SUPPLY AIR DATA

AIR FLOW 600 CFM (283 l/s) **FAN SIZE** (2) AA524-408 **ESP** 0.15 in w.c. (37 Pa) **RPM** 1550
MOTOR SIZE 1/6 HP (.12 kW) **TYPE (RPM)** See Below [1]

- [1] - HIGH STATIC (1550 Direct Drive)

AIR OPENING DATA

AIR OPENING	LOCATION	DAMPER TYPE	OPERATION
SUPPLY AIR	See Below [1]		
RETURN AIR	See Below [1]		
OUTSIDE AIR			
EXHAUST AIR			

- [1] - As per mechanical drawing

CONSTRUCTION DATA

UNIT CABINET 18 gauge satin coat galvanized sheet metal c/w 1" (25 mm) acoustical insulation on entire unit casing.
SERVICE DOOR Electrical access - screwed on lift out
DRAIN PAN Stainless steel drain pan c/w 7/8" copper fitting

- Duct collar on inlet & outlet
- Full bottom access to all components

ELECTRICAL DATA

POWER SUPPLY	MINIMUM CIRCUIT AMPACITY	MAXIMUM FUSE(D.E.)	MAXIMUM BREAKER
120 / 1 / 60	5.3 AMPS	15 AMPS	15 AMPS

- See Electrical Data Sheet for details.

FILTER SECTION DATA - Side Loaded

FILTER TYPE DAFCO Throw Away (HTP)
QTY/SIZE 1 - 10.25 x 43 x 1" (260 x 1092 x 25 mm) **QTY/SIZE**
TOTAL GROSS AREA 3.06 SQ.FT. (0.28 SQ. MTRS) **FACE VELOCITY** 196 FPM (1.00 m/s)

- Filters may be shipped loose or mounted in the tracks.

HYDRONIC HEATING COIL DATA

COIL SIZE 8.75 (222) x 42 (1067) x 2R x 12 FPI **VELOCITY** 235 FPM (1.20 m/s)
CAPACITY 17,780 Btuh (5.2 kW) **AIR P.D.** 0.07 in.wc. (17 Pa)
ENTERING AIR DB 70°F (21.1°C) **LEAVING AIR DB** 101.5°F (38.6°C)
FLUID MEDIUM Water **CONN. SIZE (In & Out)** 2 @ 7/8 in (22 mm) **FLUID P.D.** 0.8 FT (2 kPa)
FLUID FLOW RATE 1.8 US.GPM (0.1 l/s) **ENTERING FLUID TEMP** 140°F (60.0°C) **LVG. FLUID TEMP** 104.1°F (40.1°C)

- Heating coil c/w copper sweat connections.
- Heating c/w heating valve

DATE 26-Sep-2013

Continued on page 2

SUBMITTAL RECORD

JOB NAME:	U OF A OPEN LOOP RESEARCH	**JOB NO:**	E24655(E24655)
CUSTOMER:	ENGINEERED AIR SALES (EDM)	**ENGINEER:**	ROBERT PRYBYSH
EngA MODEL:	HFC-6\C	**QTY:** 6 **TAG:**	FC-1 to FC-6

HYDRONIC HEATING COIL DATA (CONTINUED)

- Coils to be flushed with hot water & T.S.P for 5 minutes
- Coils to be flushed with hot water for a further 5 minutes

COOLING COIL DATA

COIL SIZE	8.75 (222) x 42 (1067) x 2R x 12 FPI			**VELOCITY**	235 FPM (1.20 m/s)
CAPACITY	9,180 Btuh (2.7 kW)			**AIR P.D.**	0.08 in.wc. (20 Pa)
ENTERING AIR DB / WB	78°F (25.6°C) / 64.0°F (17.8°C)			**LEAVING AIR DB / WB**	62.3°F (16.8°C) / 58.7°F (14.8°C)
FLUID MEDIUM	Water	**CONN. SIZE (In & Out)**	2 @ 7/8 in (22 mm)	**FLUID P.D.**	1 FT (3 kPa)
FLUID FLOW RATE	2.2 US.GPM (0.1 l/s)	**ENTERING FLUID TEMP**	45°F (7.2°C)	**LVG. FLUID TEMP**	57.2°F (14.0°C)

- Cooling coil c/w copper sweat connections.
- Cooling c/w Cooling valve
- Coils to be flushed with hot water & T.S.P for 5 minutes
- Coils to be flushed with hot water for a further 5 minutes

SHIPPED LOOSE ITEMS (See filter section for filters)

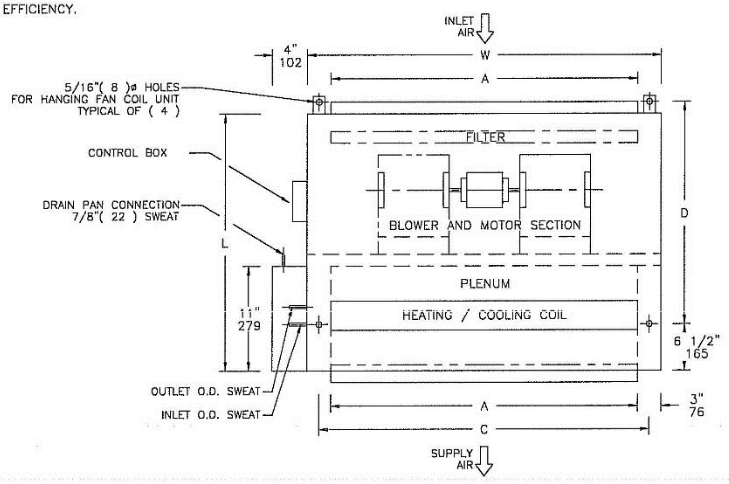
1 - Thermostat Digital ON/OFF 1H/1C (Viconics Technologies Inc VT7300C5000)

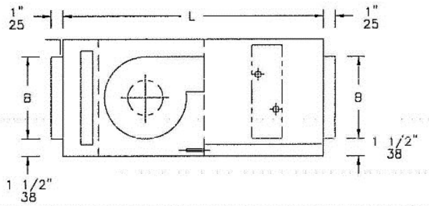
DATE 26-Sep-2013 **SUBMITTED BY** PERRY ZAPERNICK / YN

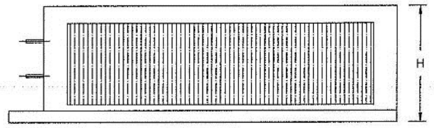
STANDARD FEATURES:

- HEAVY 18 GAUGE GALVANIZED STEEL CONSTRUCTION.
- CABINET WITH FULL 1"(25) ACOUSTICAL INSULATION.
- EXTENDED CONDENSATE DRAIN PAN WITH 7/8"(22) O.D
- HIGH PERFORMANCE 2R COOLING / 2R HEATING COIL WITH MANUAL AIR VENT.
- HEATING AND COOLING VALVE ARE UNIT MOUNTED
- DUCT COLLARS ON INLET AND OUTLET.
- FULL BOTTOM ACCESS TO ALL COMPONENTS.
- RESILIENT MOUNTED 3 SPEED PSC MOTORS 1550 RPM FOR QUIET OPERATION AND EFFICIENCY.

MODEL HFC HORIZONTAL CONCEALED
FAN COIL UNITS WITH INLET FILTERS
ARRANGEMENT 11 SHOWN







GENERAL INFORMATION, DIMENSIONS AND WEIGHTS

MODEL	NOMINAL CFM/L/S	HANDING	MOTOR HP/WATTS	MOTOR RPM	AMPS	E.S.P.	L	W	H	A	B	C	D	E	WEIGHT LBS. / KG.	FILTER
HFC-6	600 283	RIGHT	1/6 124	1550	3.7	0.15	22 559	47 1194	10 1/2 267	41 1041	8 203	44 1118	16 406	1/2 13	89 40.5	10 1/4 X 43 260 X 1092

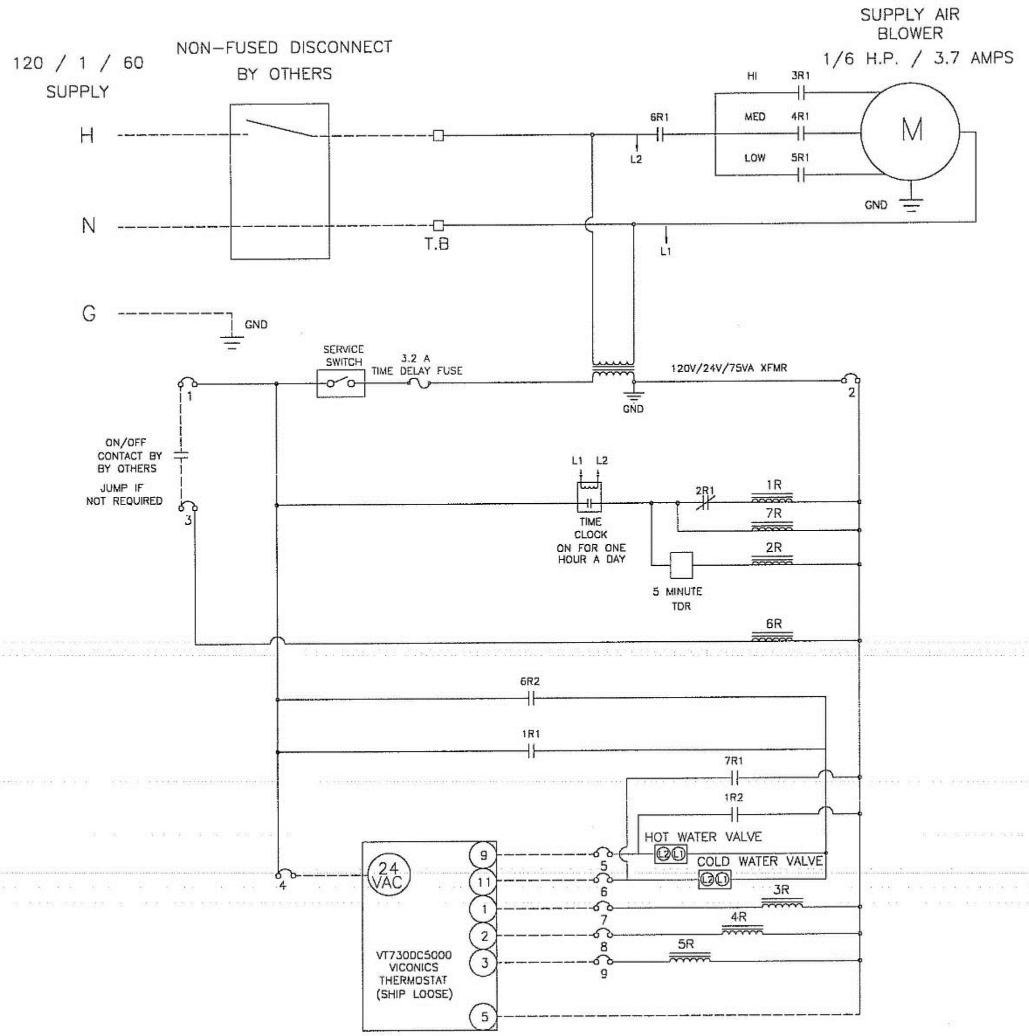
NOTES :

-UNIT SHOWN IS ARRANGEMENT 11, RIGHT HAND CONFIGURATION. DIMENSIONS ARE IN INCHES AND MILLIMETRES.

-FILTER IS REMOVABLE FROM BOTTOM.

-MAXIMUM 4ROW COIL

UNITTYPE HFC-6	TAG: FC-1,FC-2,FC-3,FC-4,FC-5 & FC-6	
REVISIONS	REVISION DATE:	REVISION BY:
DATE: SEPT 23/13	DRN.BY: YN	DRWG. No. E24655-M-01-01



--------------- DENOTES FIELD WIRING. REPLACEMENT WIRING MUST BE EQUIVALENT TO ORIGINAL WIRE SUPPLIED.

MAIN FEEDER AMPACITY: 5.3 AMPS

MAXIMUM FUSE AND BREAKER: 15 AMPS

INTERNAL WIRING DIAGRAM

TAG: FC-1 to FC-6

FC-6 HIGH STATIC MOTOR WIRING DIAGRAM

REVISIONS:

DATE:	DRN.BY:	CHKD.BY:	DRWG.NO.:
SEPT 24/13	YN		E24655-01-01

ELECTRICAL DATA

JOB NAME: U OF A OPEN LOOP RESEARCH **JOB NO:** E24655

EngA MODEL: HFC-6\C **QTY:** 6 **TAG:** FC-1 to FC-6

Power Supply	Minimum Circuit Ampacity	Terminal Block to Accept	Maximum Fuse (Dual Element)	Maximum Breaker	Minimum Unfused Conductor
120 / 1 / 60	5.3 AMPS	14 Awg	15 AMPS	15 AMPS	14 Awg

Components	Model	Minimum Conductor Size	Ampacity FLA / LRA
Supply Fan Motor	HIGH STATIC (1550 Direct Drive) 1/6 HP	14 Awg	3.7
Main Control Xfmr		14 Awg	.6
Time Clock		14 Awg	.0

WIRING DRAWING LEGEND

AFS	Auto Fan Switch	DM	Damper Motor	LAR	Low Ambient Relay
C	Contactor	FR	Fan Relay	NFD	Non Fused Disconnect
CCH	Compressor Crankcase Heater	GV1	Low Stage Gas Valve	OL	Thermal Overload
CFC	Condenser Fan Control	GV2	High Stage Gas Valve	OP	Oil Failure Switch
CLC	Compressor Loading Control	HR	Heating Relay	PV	Pilot Gas Valve
CPM	Compressor Protection Module	HLPC	High/Low Pressure Control	R	Relay or Contactor
CP	Internal Compressor Protection	HL	High Limit Control	SS	Sail Switch
CR	Cooling Relay	IGN	Ignition Control	TB	Terminal Block
CUC	Cylinder Unloading Control	LAC	Low Ambient Control	TDR	Time Delay Relay
CUS	Cylinder Unloading Solenoid	LPC	Low Pressure Control	TC	Time Clock

UNIT FUNCTION

On/off contact by others 'on' disconnect switch by others 'on', service switch 'on'.

T7300C5000 thermostat call for heating or cooling , blower starts and runs continuously.

Blower speed controlled by the thermostat.

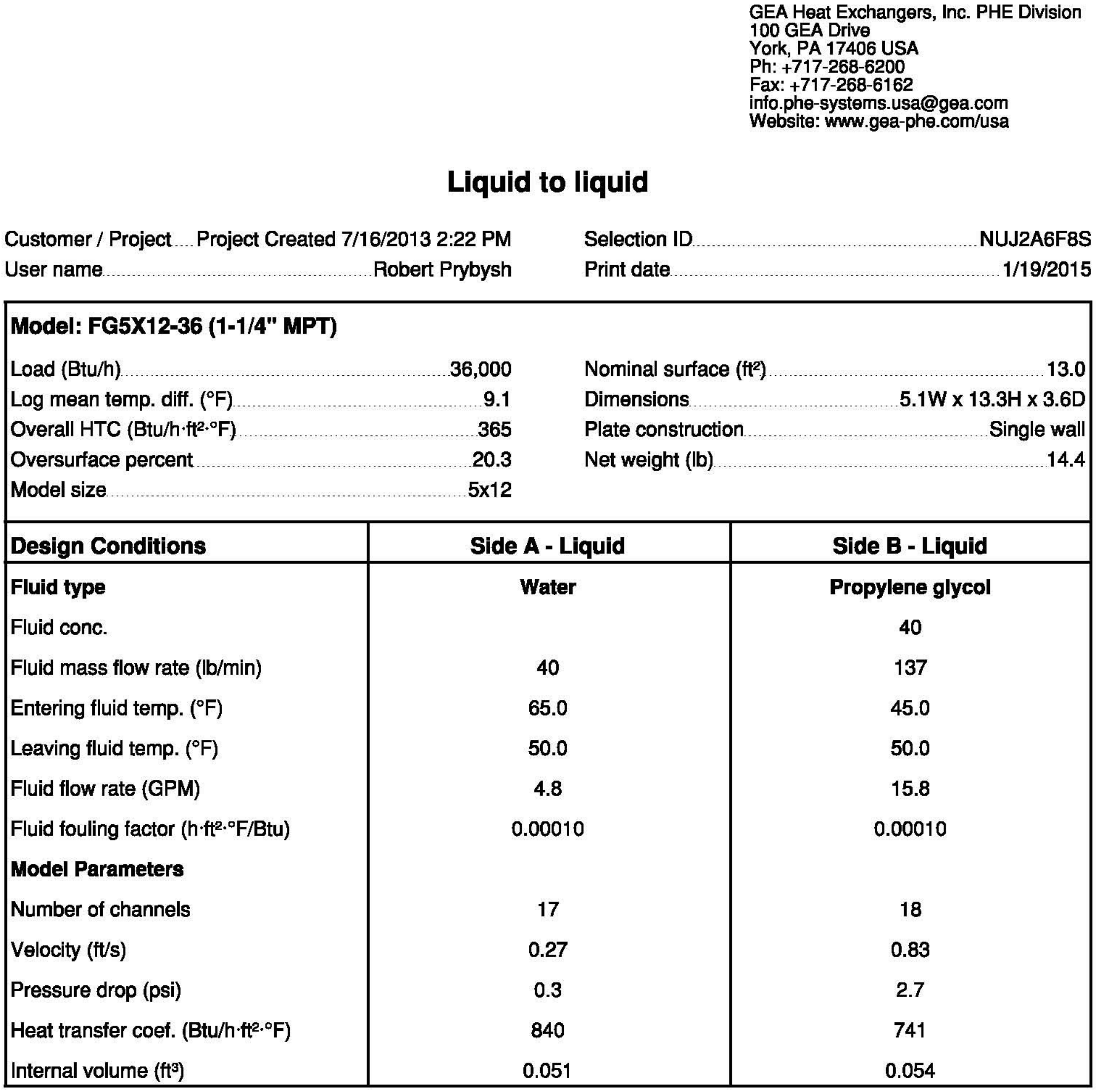
The thermostat will cycle 1 stage of heating or cooling to maintain the required room temperature.

On/Off contact off by others , disconnect switch off by others , blower stop and unit is off.

Every 24 hours, the water valve will open for 5 minutes alowing the potable water to circulate.

Note 1 - Refer to manuals shipped with unit for a more detailed explanation of maintenance, component(s) and/or controller(s).

DATE: 26-SEP-2013 **SUBMITTED BY:** PERRY ZAPERNICK / YN



GEA Heat Exchangers, Inc. PHE Division
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Website: www.gea-phe.com/usa

Liquid to liquid

Customer / Project	Project Created 7/16/2013 2:22 PM	Selection ID	NUJ2A6F8S
User name	Robert Prybysh	Print date	1/19/2015

Model: FG5X12-36 (1-1/4" MPT)

Load (Btu/h)	36,000	Nominal surface (ft^2)	13.0
Log mean temp. diff. (°F)	9.1	Dimensions	5.1W x 13.3H x 3.6D
Overall HTC (Btu/h·ft^2·°F)	365	Plate construction	Single wall
Oversurface percent	20.3	Net weight (lb)	14.4
Model size	5x12		

Design Conditions	**Side A - Liquid**	**Side B - Liquid**
Fluid type	**Water**	**Propylene glycol**
Fluid conc.		40
Fluid mass flow rate (lb/min)	40	137
Entering fluid temp. (°F)	65.0	45.0
Leaving fluid temp. (°F)	50.0	50.0
Fluid flow rate (GPM)	4.8	15.8
Fluid fouling factor (h·ft^2·°F/Btu)	0.00010	0.00010
Model Parameters		
Number of channels	17	18
Velocity (ft/s)	0.27	0.83
Pressure drop (psi)	0.3	2.7
Heat transfer coef. (Btu/h·ft^2·°F)	840	741
Internal volume (ft^3)	0.051	0.054

GEA Heat Exchangers, Inc. PHE Division
100 GEA Drive
York, PA 17406 USA
Ph: +717-268-6200
Fax: +717-268-6162
info.phe-systems.usa@gea.com
Website: www.gea-phe.com/usa

Ratings at Varying Conditions

Percent difference	**-15%**	**-7½%**	**0%**	**7½%**	**15%**
Pressure drop (psi) (Side A)	0.2	0.2	0.3	0.3	0.4
Pressure drop (psi) (Side B)	2.1	2.3	2.7	3.2	3.7
Load (Btu/h)	**30,600**	**33,300**	**36,000**	**38,700**	**41,400**
Fluid flow rate (GPM) (Side A)	4.1	4.4	4.8	5.2	5.5
Fluid mass flow rate (lb/min) (Side A)	34	37	40	43	46
Fluid flow rate (GPM) (Side B)	13.4	14.6	15.8	17.0	18.1
Fluid mass flow rate (lb/min) (Side B)	117	127	137	147	158
Entering fluid temp. (°F) (Side A)	65.0	65.0	65.0	65.0	65.0
Entering fluid temp. (°F) (Side B)	45.0	45.0	45.0	45.0	45.0
Leaving fluid temp. (°F) (Side A)	50.0	50.0	50.0	50.0	50.0
Leaving fluid temp. (°F) (Side B)	50.0	50.0	50.0	50.0	50.0
Oversurface percent	28.0	23.9	20.3	17.0	13.9

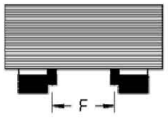
Disclaimer

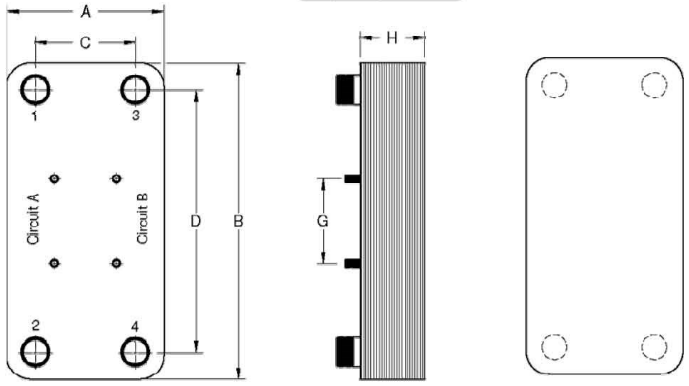
Dimension Sheet Brazed Plate Heat Exchanger

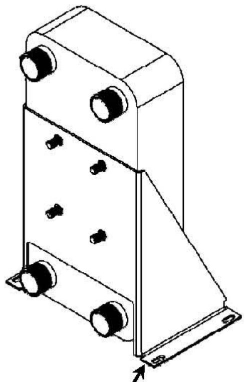
Contact:	Selection ID: NUJ2A6F8S
Customer / Project: Project Created 7/16/2013 2:22 PM	
Model Nomenclature: **FG5X12-36 (1-1/4" MPT)**	

Dimensions - inches (mm): Reference only

A:	5.08 (129.0)
B:	13.29 (337.6)
C:	2.87 (72.9)
D:	11.06 (280.9)
F:	2.48 (63.0)
G:	3.54 (89.9)
H:	3.57 (90.6)







Mounting Bracket
(optional)

Connections / Volume per BPHE

Connections				Volume per BPHE	
Circuit A		Circuit B		Circuit A	Circuit B
Position 1	Position 2	Position 3	Position 4	0.051 ft³ (1.446 L)	0.054 ft³ (1.531 L)
1-1/4" MPT	1-1/4" MPT	1-1/4" MPT	1-1/4" MPT	Net Weight: 14.4 lb (6.5 kg)	

Installation Notes:

- Pipe in counter flow direction.
- Water strainer should be installed in the fluid inlet circuit to protect the heat exchanger from blockage (20-40 mesh).
- Thread Connections – Use Teflon tape or other sealant on male threaded part of the connection to prevent leakage.

Technical Data

Standard construction materials:

Braze Alloy:	Copper 99.9%
Connector:	304 Stainless Steel
Plate:	316L Stainless Steel

Code Approvals: UL Listed, CRN pending
Optional: ASME (UM stamped), PED (CE)
Note: Code approval applies to heat exchangers only.

Allowable Working Pressure and Temperature:

Max pressure	Circuit A: 450 psig (31.0 bar ga) Circuit B: 450 psig (31.0 bar ga)
Max temperature	350.0 °F (176.7 °C)
Min temperature	-320.0 °F (-195.6 °C)

GEA PHE Systems North America, Inc.
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E-mail: info.geaphena@geagroup.com

MAC036-01-L Air-Cooled Chiller

Air-Cooled Chillers for Global
Residential and Light Commercial
Micro Climates

Rev 1.2

HVAC Guide Specifications

Air-Cooled Liquid Chiller with Low Ambient Kit
Nominal Size:
3 Tons
Multiaqua Model Number:
MAC036-01-L

Part 1-General

1.01 System Description

Multiaqua air-cooled liquid chillers are designed using scroll compressors, low sound condenser fans and high efficiency pumps.

1.02 Quality Assurance

A. Certified in accordance with U.L. Standard 95, latest version (U.S.A.).
B. Construction shall comply with ASHRAE 15 Safety Code, NEC and ASME applicable codes. (U.S.A. Codes).
C. Manufactured in a facility registered to ISO 9002, Manufacturing Quality Standard.
D. ETL Certified
E. Fully load tested at the factory.
F. Damage resistant packaging.

1.03 Delivery, Storage and Handling

A. Packaged and readied for shipment from the factory.
B. Controls shall be capable of withstanding 150°F storage temperatures in the control compartment.
C. Stored and handled per manufacturer's recommendations.

Part 2-Product

2.01 Equipment

A. General:
  1. Unit shall be a factory assembled and tested air-cooled liquid chiller.
  2. Shall be assembled on heavy gauge steel mounting/lifting rails.
  3. Contained within the unit cabinet shall be all factory wiring, piping, controls, refrigerant charge (R407c), POE oil and special accessories required prior to start up.
  4. Brass body strainer with 20 mesh screen and blow down shall be supplied in cabinet as a field installable accessory.

B. Unit Cabinet:
  1. Composed of heavy gauge galvanized steel casing with a baked polyester powder.
  2. Capable of withstanding 500-hour salt spray test in accordance with the ASTM (USA) standard.

C. Condenser Fans:
  1. 4-blade, aluminum construction and shall be dynamically balanced and corrosion resistant.
  2. Horizontal discharged air.
  3. Motors and blades shall be protected by coated steel wire safety guards.

D. Fan Motors:
  1. Condenser fan motors shall be single speed, direct drive.
  2. Totally enclosed.
  3. Permanently lubricated sleeve bearings and Class F insulation.
  4. Internal overload protection.

E. Compressors:
  1. Unit shall contain one fully hermetic scroll compressors.
  2. Direct-drive, 3500 rpm (60Hz)
  3. Compressor motor shall be suction gas cooled.
  4. Internal motor protection.
  5. Externally protected by low and high pressure cutout devices.
  6. Individual vibration isolators.

F. Pump:
   1. Integral circulating pump shall be stainless steel with high efficiency enclosed motor.
   2. Unit shall have chilled liquid solution piping to the exterior of the cabinet.

G. Evaporator:
   1. Evaporator shall have one independent refrigerant circuit and one liquid solution circuit.
   2. Rated for a refrigerant side working pressure of 450 psig and a maximum water side working pressure of 60 psig.
   3. Single pass, ANSI type 316 stainless steel, brazed plate construction.
   4. Externally insulated with closed cell, elastomeric foam. (ASTM518)

H. Condenser:
   1. Condenser coil shall be air-cooled with integral sub-cooler.
   2. One independent refrigerant circuit.
   3. Constructed of rifled copper tubing mechanically bonded to aluminum fins.
   4. Cleaned and dehydrated.
   5. Factory leak tested to 450 psig.

I. Refrigerant Circuits:
   1. Each circuit shall contain a sight glass, liquid line filter, thermal expansion valve, refrigerant charge of R407c and POE compressor oil.

<u>Part 3-Controls and Safeties</u>

3.01 Controls

A. Chiller shall be completely factory wired and tested.
B. Temperature control shall be based on leaving chilled liquid solution temperature.
   1. Temperature accuracy shall be + - 1
C. Controls shall include the following components.
   1. 24vac transformer to serve all controllers relays and control components.
   2. Microprocessor based liquid solution temperature controller.
   3. Leaving water temperature thermistor.
   4. Pump bypass timer.
   5. Compressor recycle timer.
   6. Optional low pressure bypass timer for low ambient operation.
   7. Optional fan cycling control for low ambient operation.
   8. Chilled liquid solution flow switch.

3.02 Safeties

A. Unit shall be equipped with thermistors and all necessary components in conjunction with the control system to provide the following protectants.
   1. Low refrigerant pressure.
   2. High refrigerant pressure.
   3. Low chilled liquid solution temperature.
   4. Low chilled liquid solution flow.
   5. Thermal overload.
   6. Short cycling.

<u>Part 4-Operating Characteristics:</u>

4.01 Temperatures

A. Unit shall be capable of starting and running at outdoor temperatures from 55°F to 120°F.
B. Optional Low Ambient Kit shall allow starting and running at outdoor temperatures to -20°F. A field supplied and installed crankcase heater must be used when operating at these temperatures.
C. Unit shall be capable of starting up with a maximum 80°F and a sustained 70°F entering fluid solution temperature to the evaporator.
C. <u>Minimum 10% Glycol solution is always required</u>.
D. For outdoor temperatures below 32°F, reference MAC Glycol Solution Data table.

These specifications are subject to change without notice.
Check www.multiaqua.com for the latest information.

4.02 Electrical Requirements

A. Primary electrical power supply shall enter the unit at a single location.
B. Electrical power supply shall be rated to withstand 120°F operating ambient temperature.
C. Units shall be available in 1 or 3-phase power at the voltages shown in the equipment electrical data.
D. Control points shall be accessed through terminal block.

Part 5- Definitions:

5.01 Abbreviations

A. CFM = Cubic Feet per Minute
B. DB = Dry Bulb Temperature
C. EWT = Entering Water Temperature
D. GPM = US Gallons Per Minute
E. MBH = BTU X 1000
F. SC = Sensible Cooling
G. TC = Total Cooling = Sensible + Latent
H. WB = Wet Bulb Temperature
I. WPD = Water Pressure Drop in feet of head
J. dB = Decibel Level
K. m = Meter

5.02 Measurements

A. All measurements with regard to length, width, and height shall be in inches.

MAC036-01-L Product Specifications

Physical Data										
Model Number	Coil				Chiller				Weight (lbs.)	
	Height (in)	Length (in)	Copper Diameter (in)	Coil Rows	Height (in)	Length (in)	Width (in)	Refrigerant R407c	Net	Shipping
MAC036-1-L	38	48	3/8	1	49.75	39.75	16.25	80.00 oz.	280	283

Model Number	Volts/ Phase/ Hertz	Compressor		Condenser Fan Motor (2 Qty)		Pump Motor		Fuse or HACR Circuit Breaker Per Circuit	
		(RLA)	(LRA)	(FLA)	(RPM)	(FLA)	(RPM)	MCA	MOP
MAC036-1-L	208/230-1-50/60	18.4	95	1.05	1050	3.70	3450	28.80	45

	MAC036-1-L
Compressor	Copeland Scroll
Refrigerant	R407c
Heat Exchanger	Brazed Plate
Max. Pump Head Pressure	50 ft. of head
Max Flow Rate	8.6 gpm
Min Flow Rate	5.5 gpm
Supply Water Temp	44°
Return Water Temp	54°
Min. Solution Content	25 Gallons
Expansion Tank Size	2 Gallons
Pump*	0.5 HP
Water Connections	1" S & 1.25" R
Internal Pressure loss	1.77 ft. of head

*Internal Pump Included

Multiaqua chillers are designed to operate exclusively with R407c refrigerant in a self-contained, pre-charged refrigerant system. Do not access the closed refrigerant circuit for any reason other than after-sale, after installation component replacement. Routine maintenance and service is to be performed by qualified personnel only.

MAC036-01-L Product Specifications

MAC036-01-L Capacity / Watts / EER / COP*				
O/A Temp (°F)	MAC036			
	Tons	KW	EER	COP
82	2.9	3.3	10.55	3.09
95	2.8	3.6	9.33	2.80
100	2.7	3.9	8.31	2.43
105	2.7	4.0	8.10	2.37
110	2.6	4.3	7.28	2.13

* The following equation was used to calculate COP values other than ARI conditions: COP = EER x .2928

Glycol Solution Data				
Propylene Glycol %	Water Flow	Capacity	Min. Ambient Temp	GPM Adjustment= 100% Capacity
10%	x 1.020	x 0.99	26°F	x 1.01
20%	x 1.028	x 0.98	18°F	x 1.03
30%	x 1.036	x 0.98	8°F	x 1.07
40%	x 1.048	x 0.97	-7°F	x 1.11
50%	x 1.057	x 0.96	-29°F	x 1.16

**** A minimum of ten percent propylene glycol even in areas where there is no danger of freezing.**

Example: 30% glycol solution.
Maximum Flow Rate = 8.6 gpm x 1.036
System capacity x .98
Use Propylene Glycol Only

Important

If the outside temperature is expected to fall below freezing (32°F) in the area the Multiaqua chiller is to be installed; the installer must take the following precautions. Failure to do so will void the warranty.
To not engage in cold ambient mitigation will result in the failure of components such as the heat exchanger, compressor, piping, circulating pump, etc… and or property damage.

- Keep the liquid solution at a minimum of ten percent propylene glycol even in climates where there is no danger of freezing.
- The additional percentage amount of glycol recommended is dependent on the expected ambient temperatures and the solution makeup recommendation of the glycol manufacturer. Refer to the Glycol Solution Data table above.
- Ensure the system circulating pump is in a constant energized mode to keep a continuous circulation of liquid solution.

The Multiaqua chiller is a self-contained air-cooled condenser, coupled with an insulated brazed plate heat exchanger (evaporator). The system utilizes a scroll compressor to circulate refrigerant between the condenser and heat exchanger. The refrigerant is metered into the heat exchanger with a thermostatic expansion valve. Protecting the system are high and low pressure switches as well as a pump flow switch.
Liquid solution (water and propylene glycol; minimum 10 % is required) is circulated through the heat exchanger by an externally mounted pump. The liquid solution flows through the heat exchanger to the system supply piping and on to the air handlers.
Low ambient kits are available for operating ambient temperatures down to 0 degrees Fahrenheit. The low ambient kits consist of an ICM 325 (+) ICM (175) for all chillers.

MAC036-01-L Cooling Performance Data

MAC036 CAPACITIES with 0% Glycol

LWT (°F)	ENTERING AIR TEMPERATURE (°F)									
	82		95		100		105		110	
	TONS	GPM	TONS	GPM	TONS	GPM	TONS	GPM	TONS	GPM
35	1.70	7.2	1.60	7.2	1.50	7.2	1.40	7.2	1.30	7.2
40	2.30		2.20		2.10		2.10		2.00	
42	2.60		2.50		2.40		2.40		2.30	
44	2.90		2.80		2.70		2.70		2.60	
45	3.10		3.00		2.90		2.80		2.70	
46	3.20		3.10		3.00		3.00		2.90	
48	3.60		3.50		3.20		3.30		3.20	
50	3.90		3.80		3.50		3.60		3.50	
55	4.80		4.70		4.30		4.30		4.20	
60	5.80		5.60		5.20		5.20		5.00	

MAC036 CAPACITIES with 10% Glycol

LWT (°F)	ENTERING AIR TEMPERATURE (°F)									
	82		95		100		105		110	
	TONS	GPM	TONS	GPM	TONS	GPM	TONS	GPM	TONS	GPM
35	1.68	7.2	1.58	7.2	1.49	7.2	1.39	7.2	1.29	7.2
40	2.28		2.18		2.08		2.08		1.98	
42	2.57		2.48		2.38		2.38		2.28	
44	2.87		2.77		2.67		2.67		2.57	
45	3.07		2.97		2.87		2.77		2.67	
46	3.17		3.07		2.97		2.97		2.87	
48	3.56		3.47		3.17		3.27		3.17	
50	3.86		3.76		3.47		3.56		3.47	
55	4.75		4.65		4.26		4.26		4.16	
60	5.74		5.54		5.15		5.15		4.95	

MAC036 CAPACITIES with 20% Glycol

LWT (°F)	ENTERING AIR TEMPERATURE (°F)									
	82		95		100		105		110	
	TONS	GPM	TONS	GPM	TONS	GPM	TONS	GPM	TONS	GPM
35	1.67	7.2	1.57	7.2	1.47	7.2	1.37	7.2	1.27	7.2
40	2.25		2.16		2.06		2.06		1.96	
42	2.55		2.45		2.35		2.35		2.25	
44	2.84		2.74		2.65		2.65		2.55	
45	3.04		2.94		2.84		2.74		2.65	
46	3.14		3.04		2.94		2.94		2.84	
48	3.53		3.43		3.14		3.23		3.14	
50	3.82		3.72		3.43		3.53		3.43	
55	4.70		4.61		4.21		4.21		4.12	
60	5.68		5.49		5.10		5.10		4.90	

MAC036-01-L Cooling Performance Data

MAC036 CAPACITIES with 30% Glycol

LWT (°F)	ENTERING AIR TEMPERATURE (°F)									
	82		95		100		105		110	
	TONS	GPM	TONS	GPM	TONS	GPM	TONS	GPM	TONS	GPM
35	1.67	7.2	1.57	7.2	1.47	7.2	1.37	7.2	1.27	7.2
40	2.25		2.16		2.06		2.06		1.96	
42	2.55		2.45		2.35		2.35		2.25	
44	2.84		2.74		2.65		2.65		2.55	
45	3.04		2.94		2.84		2.74		2.65	
46	3.14		3.04		2.94		2.94		2.84	
48	3.53		3.43		3.14		3.23		3.14	
50	3.82		3.72		3.43		3.53		3.43	
55	4.70		4.61		4.21		4.21		4.12	
60	5.68		5.49		5.10		5.10		4.90	

MAC036 CAPACITIES with 40% Glycol

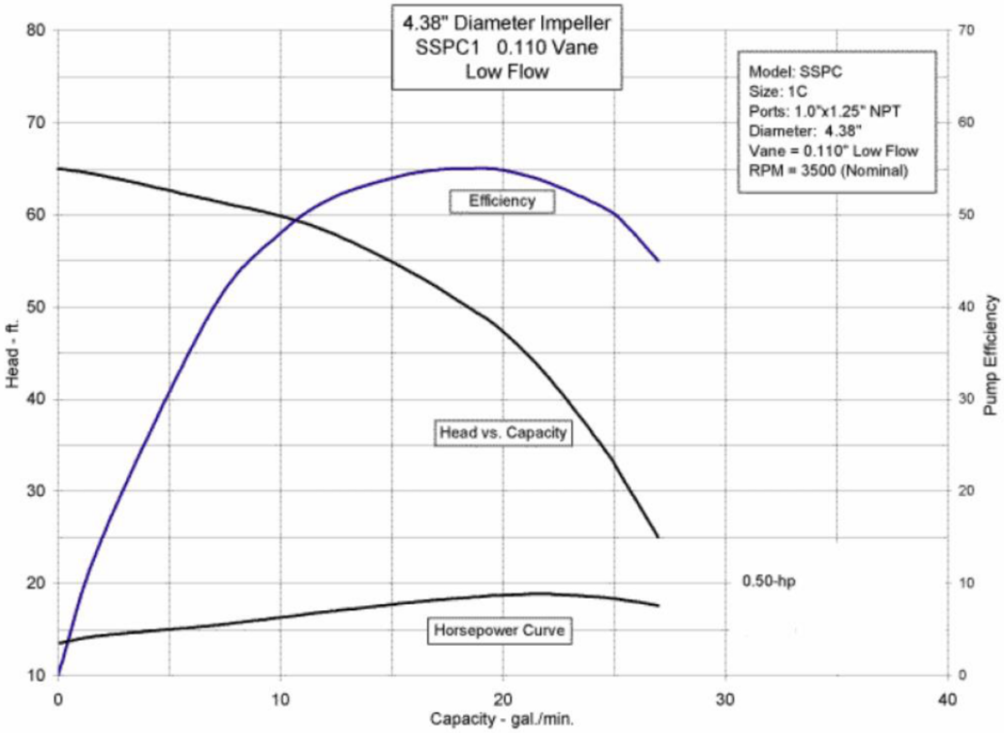
LWT (°F)	ENTERING AIR TEMPERATURE (°F)									
	82		95		100		105		110	
	TONS	GPM	TONS	GPM	TONS	GPM	TONS	GPM	TONS	GPM
35	1.65	7.2	1.55	7.2	1.46	7.2	1.36	7.2	1.26	7.2
40	2.23		2.13		2.04		2.04		1.94	
42	2.52		2.43		2.33		2.33		2.23	
44	2.81		2.72		2.62		2.62		2.52	
45	3.01		2.91		2.81		2.72		2.62	
46	3.10		3.01		2.91		2.91		2.81	
48	3.49		3.40		3.10		3.20		3.10	
50	3.78		3.69		3.40		3.49		3.40	
55	4.66		4.56		4.17		4.17		4.07	
60	5.63		5.43		5.04		5.04		4.85	

MAC036 CAPACITIES with 50% Glycol

LWT (°F)	ENTERING AIR TEMPERATURE (°F)									
	82		95		100		105		110	
	TONS	GPM	TONS	GPM	TONS	GPM	TONS	GPM	TONS	GPM
35	1.63	7.2	1.54	7.2	1.44	7.2	1.34	7.2	1.25	7.2
40	2.21		2.11		2.02		2.02		1.92	
42	2.50		2.40		2.30		2.30		2.21	
44	2.78		2.69		2.59		2.59		2.50	
45	2.98		2.88		2.78		2.69		2.59	
46	3.07		2.98		2.88		2.88		2.78	
48	3.46		3.36		3.07		3.17		3.07	
50	3.74		3.65		3.36		3.46		3.36	
55	4.61		4.51		4.13		4.13		4.03	
60	5.57		5.38		4.99		4.99		4.80	

MAC036-01-L Chiller Pump Curve
Pump Model Numbers

SSP-1 = 208/230-1-50/60
SSP-2 = 208/230/460-3-50/60
0.5 Horsepower

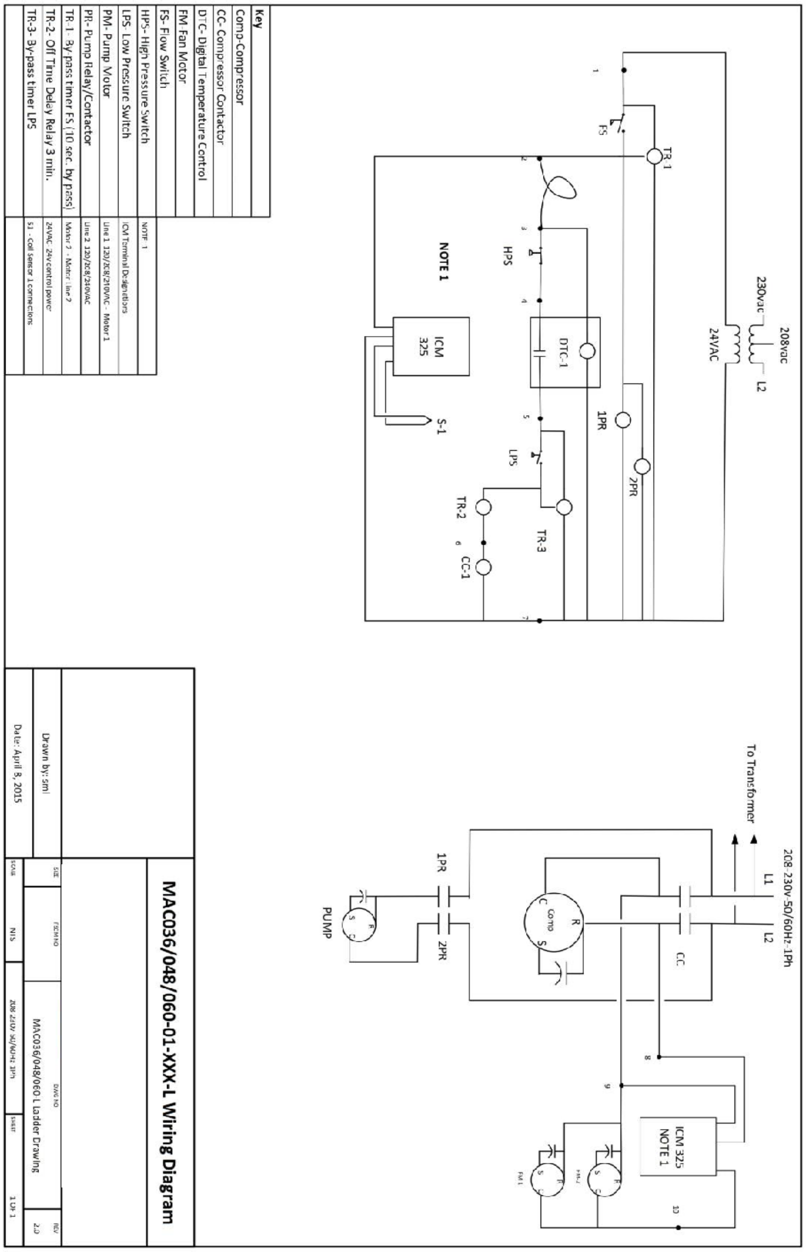


MAC036-01-L Sound Data

MODEL #	MAC036-01-L
Fan Speed	dB @ 1 m
H	69

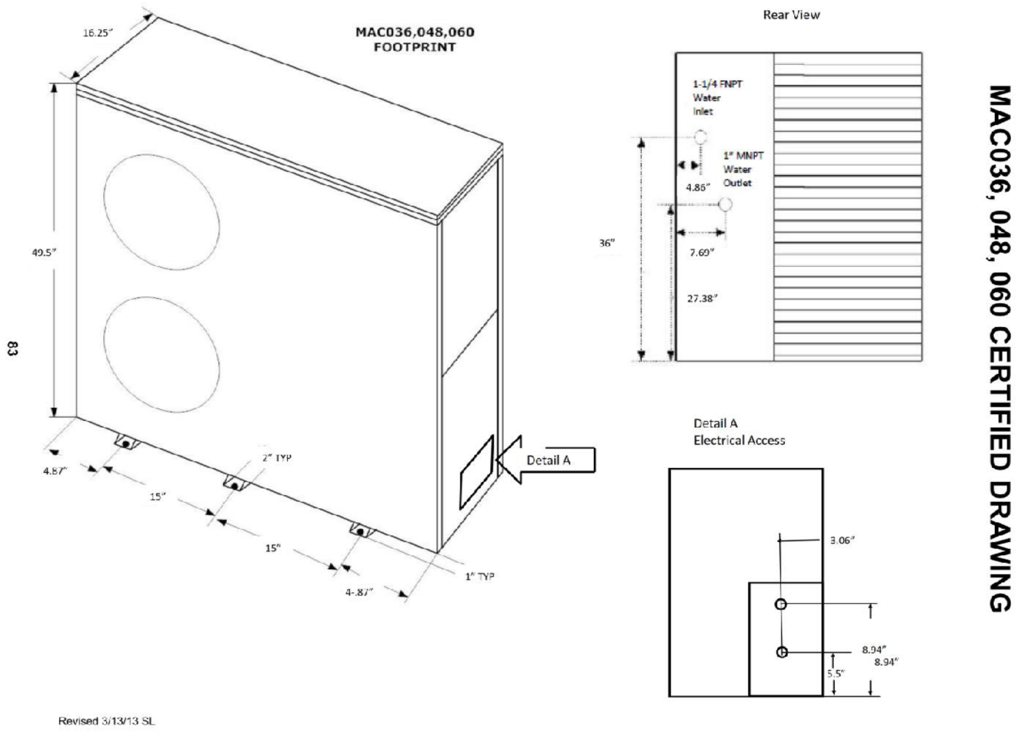
These specifications are subject to change without notice.
Check www.multiaqua.com for the latest information.

MAC036-01-L Wiring Diagram



These specifications are subject to change without notice.
Check www.multiaqua.com for the latest information.
11

MAC-036-01-L Dimensional Drawing



Multiaqua Inc.
306 Hagood Street
Easley, SC 29640
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Fax: 864-850-8995
www.multiaqua.com

For Technical Assistance:

1-855-THNK-WTR (1-855-846-5987)

These specifications are subject to change without notice.
Check www.multiaqua.com for the latest information.

APPENDIX B: Standard Methods FPA Documents and Summary Sheets

The documentation contained within this appendix was tabulated by Olisaemaka Osolu (Jeremiah Osolu) under direction from Robert Prybysh with the intent of summarizing the requirements for completing a Flavour Profile Analysis.

RECRUITMENT PROCEDURE

- SCDEHULED INFORMATIVE SEMINAR DATE
- INFORMATIVE POSTERS TO WARRANT INTEREST
- PANELIST APPLICATION FORM (NAME, EMAIL AND CELL NUMBER COLLECTION)
- QUESTIONNAIRES HANDOUT
- COORDINATED PERSONAL INTERVIEW WITH INTERESTED APPLICANTS
- SCREENING TEST
- PANELIST SELECTION
- TRAINING OF PANELISTS

PREPARATION FOR RECRUITMENT:

What to involve in posters seminars and personal contact

- Screening Objective – *testing of odor and taste of water **(FPA)***
- Time Commitment – *20 to 30 minutes per week*
- Duration of test – *15 minutes per session*
- General procedure description
- Merits of training

Recruitment criteria / Questionnaire topics:

- Background information
- Interests – importance of sensory testing
- Availability – (since minimum of 80% attendance os required)
- Promptness – should be facilitated with advance notice of all tests (personal reminders telephone call)
- Health – check for allergies and other indispositions
- Articulateness – good communication skills required for description tests
- Smoking
- Age
- Sensory experience

Guidelines for interviewer:

- Knowledge and experience of sensory evaluation
- Prepare list of questions and points to be covered
- Questions should follow a logical order (grouping of questions)
- Should listen and take notes

References:

1. *Guidelines For The Selection And Training Of Sensory Panel Members / Sponsored By ASTM Committee E-18 On Sensory Evaluation Of Materials And Products. n.p.: Philadelphia, Pa. (1916 Race St., Philadelphia 19103) : American Society for Testing and Materials, c1981., 1981. NEOS's Catalog. Web. 3 Dec. 2013.*
2. *American Water Works Association. "Flavor Profile Analysis: Screening and Training of Panelists." AWWA Manual. American Water Works Assoc., Denver, CO (1993).*

SCREENING GUIDELINES

- A PANEL SHOULD CONSIST OF 5 PANELIST OR A MINIMUM OF 4 PANELIST INCLUDING THE PANEL LEADER
- THREE TIMES AS MANY PANELISTS WILL BE NEEDED FOR DISCRIMINATION TEST
- THE SCREENING TEST METHOD SHOULD BE SIMILAR TO THE ACTUAL TEST
- THE SCREENING TEST IS DESIGNED SO THAT A SPECTRUM OF SENSORY DIFFERENCES PROGRESSING FROM LARGE TO SMALL IS INCLUDED
- CANDIDATES SHOULD CLEARLY UNDERSTAND EACH TEST METHOD AND SCORE SHEET
- TEST SHOULD BE REPEATED TO DETERMINE THE REPRODUCIBILITY OF CANDIDATES RESPONSES
- DATA FROM PERSONAL INTERVIEW AND QUESTIONNAIRE SHOULD PROVIDE INTEREST, AVAILABILITY, PERSONALITY AND GENERAL HEALTH OF PANELISTS
- SELECTION SHOULD BE BASED ON QUESTIONNAIRE PERSONAL INTERVIEW AND FLAVOR SCREENING TEST

References:

Guidelines For The Selection And Training Of Sensory Panel Members / Sponsored By ASTM Committee E-18 On Sensory Evaluation Of Materials And Products. n.p.: Philadelphia, Pa. (1916 Race St., Philadelphia 19103) : American Society for Testing and Materials, c1981., 1981. NEOS's Catalog. Web. 3 Dec. 2013

SCREENING TEST

ODOR TEST INSTRUCTIONS

- A SET OF SAMPLES WILL BE PRESENTED
- FOR EACH SAMPLE, SHAKE FLASK VIGOROUSLY FIVE TIMES IN VERTICAL DIRECTION AND OPEN CLOSE TO NOSE
- TAKE THREE SHORT SNIFFS AND MOVE UNTO NEXT SAMPLE
- SNIFF ODOR FREE WATER AND REST 2 MINUTES BETWEEN SAMPLES
- MEMORIZE DESCRIPTORS
- ANOTHER SET OF UNLABELLED SAMPLES WILL BE PRESENTED
- PERFORM THE FIRST THREE STEPS FOR THE __ SAMPLES
- RECORD RESULTS IN THE ODOUR SHEETS PROVIDED
- SAMPLES CAN BE RETESTED FOR CONFIRMATION *(1ST IMPRESSION IS USUALLY THE MOST ACCURATE)*
- RECORD PERCEIVED INTENSITIES *(USE RECORD SHEETS AS GUIDE)*

❖ **FOLLOW NEXT SET OF INSTRUCTIONS WHEN INFORMED**

TASTE TEST INSTRUCTIONS

- TASTE THE FOUR SAMPLES PRESENTED
- USE CRACKERS BETWEEN SAMPLES TO REDUCE CARRYOVER OF PERCEPTION
- MEMORIZE THE DESPCRIPTORS AS SEEN ON THE LABEL
- ANOTHER SET OF 6 UNLABELLED SAMPLES WILL BE PRESENTED
- TASTE EACH SAMPLE AND RECORD THE DESCRIPTOR OF EACH SAMPLE IN THE TASTE SHEETS PROVIDED

- **FOLLOW NEXT SET OF INSTRUCTIONS WHEN INFORMED**

INTENSITY TEST INSTRUCTIONS

- TASTE AND RECORD EACH SAMPLE PRESENTED
- RECORD THE DESCRIPTOR AND INTENSITY OF EACH SAMPLE

REFERENCES

1. Bartels, Jeroen HM, Brian M. Brady, and Irwin H. Suffet. "Training panelists for the flavor profile analysis method." *Journal of the American Water Works Association* 79.1 (1987): 26-32.
2. Guidelines For The Selection And Training Of Sensory Panel Members / Sponsored By ASTM Committee E-18 On Sensory Evaluation Of Materials And Products. n.p.: Philadelphia, Pa. (1916 Race St., Philadelphia 19103) : American Society for Testing and Materials, c1981., 1981. NEOS's Catalog. Web. 3 Dec. 2013.

ANALYSIS AND INTERPRETATION OF SCREENING TEST

1. TASTE TEST

- EACH BASIC TASTE MUST BE CORRECTLY IDENTIFIED
- A SCORE OF A 100 PERCENT IS REQUIRED

2. ODOR RECOGNITION TEST

GRADE CANDIDATES ACCORDING TO PERFORMANCE AS FOLLOWS

- 5 POINTS FOR IDENTIFICATION (example: Decanal)
- 3 POINTS FOR CHARACTERIZATION (example: fruity Orange-like for Decanal)
- 1 POINT FOR ATTEMPTED DESCRIPTIONS (example: sweet for Decanal)
- A SCORE OF 70 PERCENT IS DESIRABLE

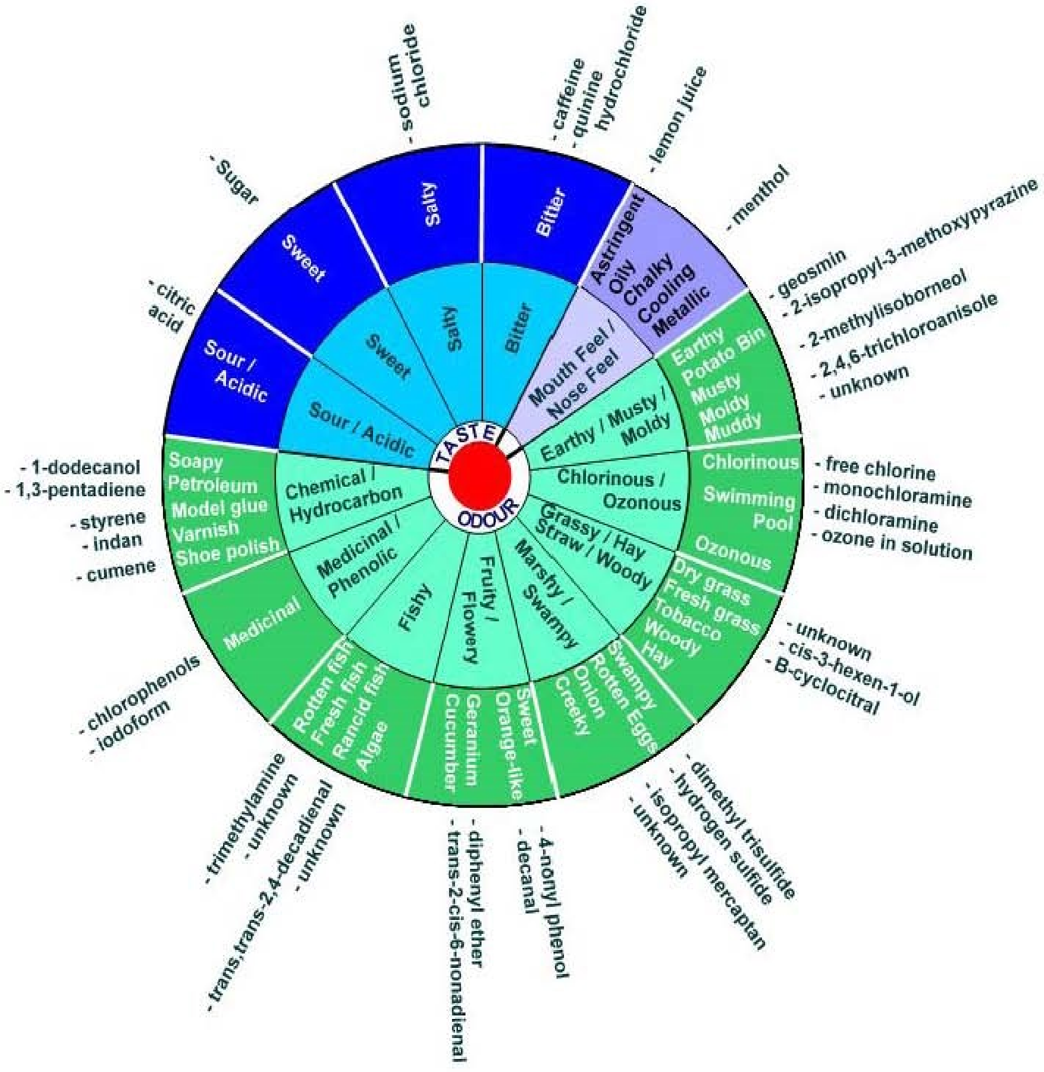
3. INTENSITY RANKING

- PERFORMANCE OF TASTER SHOULD BE COMPARED WITH THAT OF THE GROUP BY FINDING DEVIATION FROM AVERAGE BY ANALYSIS OF VARIANCE
- LOW DEVIATION DOES NOT MEAN RELIABLE JUDGE. IT CAN ALSO INDICATE LACK OF DISCRIMINATION BETWEEN SAMPLES
- IF MEAN SCORES ARE DIFFERENT AND THERE ID LOW DEVIATION THEN JUDGMENT IS RELIABLE
- ANALYST WITH BELOW 5 PERCENT SIGNIFICANCE SHOULD BE DISCARDED

References:

ASTM Committee E-18, comp. Guidelines for the Selection and Training of Sensory Panel Members. Philadelphia: ASTM, 1981. Print.

ODOUR AND TASTE REFERENCE CHART



03.87 A: Flavour Profile Analysis Sheet
Date:
Name :

ID #	Descriptor	Intensity
0		
1		
2		
3		
4		
5		
6		
7		
8		
9		

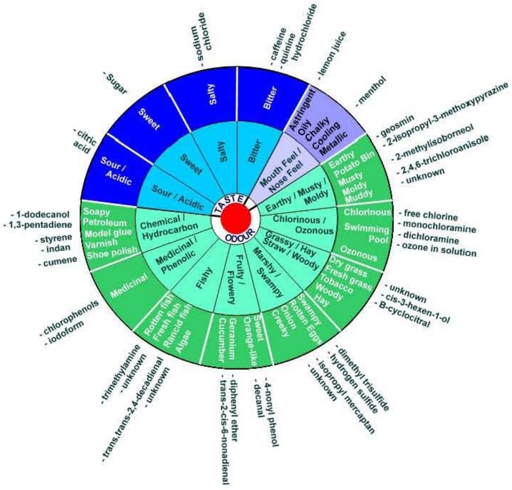
ID #	Sample
0	
1	
2	
3	
4	
5	
6	
7	
8	
9	

NOTE : samples at 25°C

Intensity Rating:

0 - no odour detected
0.25 - trace (unidentifiable odour)
0.5 - slight identifiable odour
1.0 - slightly objectional odour
2.0 - moderately objectional odour
3.0 - objectional odour (not drinkable)

Reference Chart



03.87 A: Flavour Profile Analysis Sheet

Date:

Name :

ID #	Descriptor	Intensity
0		
1		
2		
3		
4		
5		
6		
7		
8		
9		

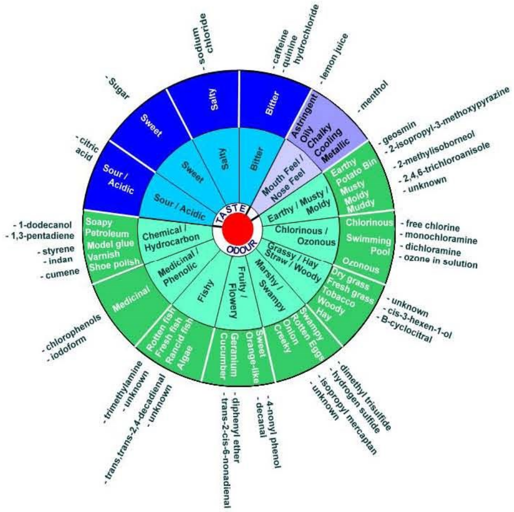
ID #	Sample
0	
1	
2	
3	
4	
5	
6	
7	
8	
9	

NOTE : samples at 25°C

Intensity Rating:

0 - no taste detected
0.25 - trace (unidentifiable taste)
0.5 - slight identifiable taste
1.0 - slightly objectional taste
2.0 - moderately objectional taste
3.0 - objectional taste (not drinkable)

Reference Chart



03.87 A: Flavour Profile Analysis Sheet

Date:

Name :

ID #	Descriptor	Intensity
0		
1		
2		
3		
4		
5		
6		
7		
8		
9		

ID #	Sample
0	
1	
2	
3	
4	
5	
6	
7	
8	
9	

NOTE : samples at 25°C

Intensity Rating:

0 - no taste detected
0.25 - trace (unidentifiable taste)
0.5 - slight identifiable taste
1.0 - slightly objectional taste
2.0 - moderately objectional taste
3.0 - objectional taste (not drinkable)

03.87 A: Flavour Profile Analysis Sheet

Date:

Name :

ID #	Descriptor	Intensity
0		
1		
2		
3		
4		
5		
6		
7		
8		
9		

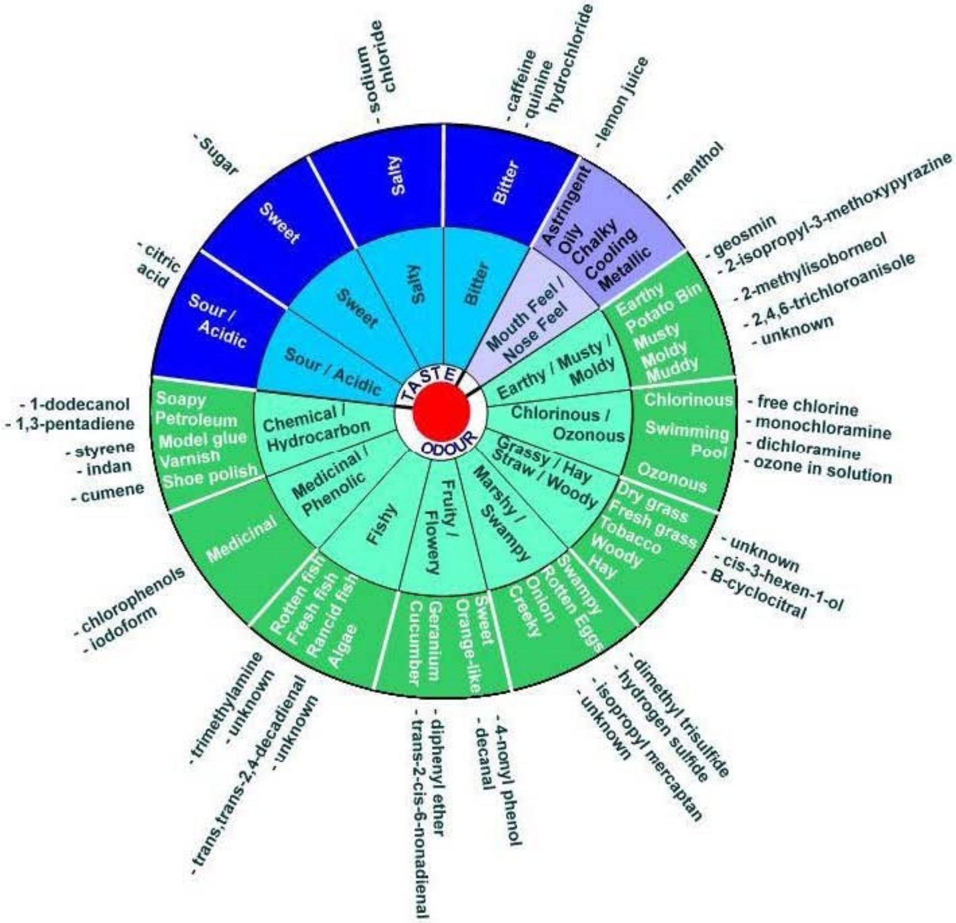
ID #	Sample
0	
1	
2	
3	
4	
5	
6	
7	
8	
9	

NOTE : samples at 25°C

Intensity Rating:

0 - no odour detected
0.25 - trace (unidentifiable odour)
0.5 - slight identifiable odour
1.0 - slightly objectional odour
2.0 - moderately objectional odour
3.0 - objectional odour (not drinkable)

REFERENCE CHART



The inner wheel indicates categories, the middle wheel indicated descriptors, and the outer wheel indicates reference standards. The distribution system

Reference:

Khiari, Djanette. "AWWA's Taste And Odor Committee." *Journal: American Water Works Association* 96.2 (2004): 32-36. *Environment Complete*. Web. 3 Dec. 2013.

EXPECTATION OF PANEL LEADER

A PANEL LEADER SHOULD

- BE TRAINED AND EXPERIENCED IN DESCRIPTIVE METHODS
- ARRANGE SAMPLES SUCH THAT SAMPLES KNOWN TO BE FATIGUING ARE PLACED NEAR THE END OF THE SAMPLE ROW
- AVOID JUXTAPOSITION OF SAMPLES
- PLACE TASTE FREE AND ODOR FREE BLANKS BETWEEN SAMPLES
- ATTEMPT TO GROUP PANELISTS RESPONSES TOGETHER
- SOLICIT COMMENTS FROM OTHER PANELISTS AS TO WHETHER OR NOT THEY AGREE WITH THE DESCRIPTIONS
- ENSURE THAT EACH PANELIST IS PROVIDED WITH STANDARDS THAT DUPLICATE THE SAMPLE AROMAS

REFERENCES

1. *Bartels, Jeroen HM, Brian M. Brady, and Irwin H. Suffet. "Training panelists for the flavor profile analysis method." Journal of the American Water Works Association 79.1 (1987): 26-32.*

2. *Guidelines For The Selection And Training Of Sensory Panel Members / Sponsored By ASTM Committee E-18 On Sensory Evaluation Of Materials And Products. n.p.: Philadelphia, Pa. (1916 Race St., Philadelphia 19103) : American Society for Testing and Materials, c1981., 1981. NEOS's Catalog. Web. 3 Dec. 2013.*

3. *American Water Works Association. "Flavor Profile Analysis: Screening and Training of Panelists." AWWA Manual. American Water Works Assoc., Denver, CO (1993).*

EXPECTATIONS OF PANELISTS

- PANELISTS SHOULD NOT WEAR PERFUME OR AFTER SHAVE, EAT, DRINK OR SMOKE FIFTEEN (15) MINUTES PRIOR TO TESTING
- PANELISTS SHOULD REPORT COLD OR SINUS PROBLEMS BEFORE TEST
- PANELISTS SHOULD WASH THEIR HANDS WITH NON- ODOROUS SOAP BEFORE TEST
- PANELIST SHOULD GIVE NOTIFICATION OF ABSENCE WELL IN ADVANCE OF TEST
- PANELISTS SHOULD ADHERE STRICTLY TO GIVEN INSTRUCTIONS
- PANELISTS SHOULD NOT DISCUSS DECISIONS ON DESCRIPTIONS AND INTENSITY UNTIL GENERAL DISCUSSION IS CALLED

Reference:

Bartels, Jeroen HM, Brian M. Brady, and Irwin H. Suffet. "Training panelists for the flavor profile analysis method." Journal of the American Water Works Association 79.1 (1987): 26-32.

SCREENING TEST LAB PREPARATION

APPARATUS

- PLASTIC CUPS AND ERLEMNEYER FLASKS SHOULD BE WASHED WITH SOAPY WATER
- SCRUB OUTSIDE THE FLASKS AND CUPS TO REMOVE BODY OILS
- RINSE 10 TIMES WITH HOT WATER AND THREE TIMES WITH ODOR FREE WATER
- TO STORE FLASK ADD 100 mL ODOR FREE WATER AND STOPPER
- BEFORE USE, RINCE WITH ODOR FREE WATER
- CHECK FOR RESIDUAL ODOR AND REPEAT CLEANING IF ODOR IS OBSERVED

TASTE SAMPLE PREPARATION

- SWEET, SOUR, SALT AND BITTER STOCK SOLUTIOINS SHOULD BE PREPARED IN PLASTIC CUPS IN THE FOLLOWING CONCENTRATIONS
  - SWEET: SUGAR (*reagent grade* ***5%, 10%, AND 15% CONCENTRATION)***
  - SOUR: CITRIC ACID (*reagent grade* ***0.05%, 0.10,% AND 0.20% CONCENTRATION***)
  - SALTY: SODIUM CHLORIDE ***(****reagent grade* ***0.4%, 0.7%, AND 1.0% CONCENTRATION)***
  - BITTER: QUINNINE HYDROCHLORIDE DIHYDRATE OR CAFFEINE ***(0.05%, 0.1%, AND 0.2%)***

NOTE*: ALL SAMPLES SHOULD BE AT 25°C*

- ONE OF EACH SAMPLE SHOULD BE LABELLED AND PRESENTED TO PANELIST FOR MEMORIZATION
- ON COMPLETION OF TASK, STOCK SOLUTION SHOULD BE REMOVED FOR TEST TO BEGIN

TASTE ANALYSIS

- PREPARE A ROW OF SIX SAMPLES WITHOUT LABELS FOR EACH PANELIST ONE OF EACH STOCK SOLUTION ONE ODOR AND TASTE FREE WATER AND ONE TASTE REPLICATE
- A TASTE RECORD SHEET SHOULD BE PROVIDED TO EACH PANELIST
- CRACKERS SHOULD BE PROVIDED TO REDUCE CARRYOVER OF PERCEPTION

ODOR SAMPLE PREPARATION

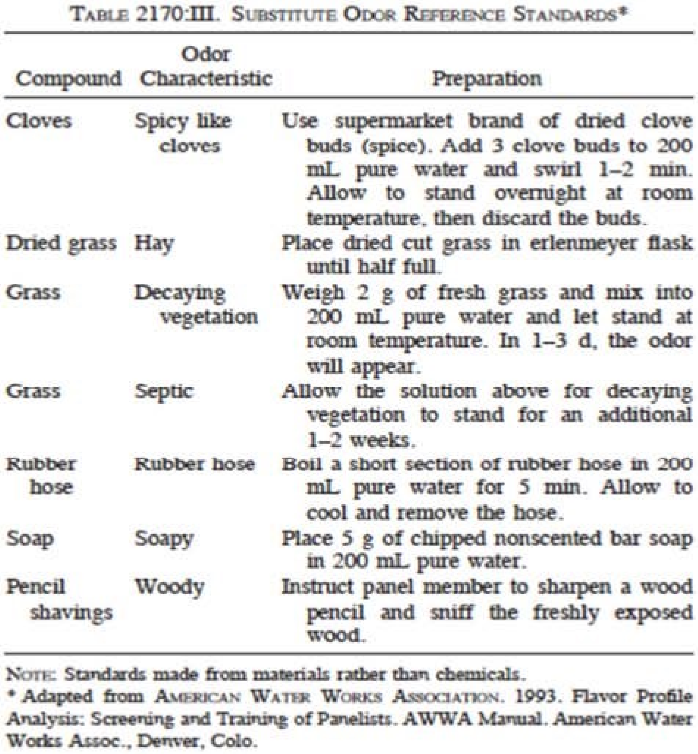


TABLE 2170:III. SUBSTITUTE ODOR REFERENCE STANDARDS*

Compound	Odor Characteristic	Preparation
Cloves	Spicy like cloves	Use supermarket brand of dried clove buds (spice). Add 3 clove buds to 200 mL pure water and swirl 1–2 min. Allow to stand overnight at room temperature, then discard the buds.
Dried grass	Hay	Place dried cut grass in erlenmeyer flask until half full.
Grass	Decaying vegetation	Weigh 2 g of fresh grass and mix into 200 mL pure water and let stand at room temperature. In 1–3 d, the odor will appear.
Grass	Septic	Allow the solution above for decaying vegetation to stand for an additional 1–2 weeks.
Rubber hose	Rubber hose	Boil a short section of rubber hose in 200 mL pure water for 5 min. Allow to cool and remove the hose.
Soap	Soapy	Place 5 g of chipped nonscented bar soap in 200 mL pure water.
Pencil shavings	Woody	Instruct panel member to sharpen a wood pencil and sniff the freshly exposed wood.

NOTE: Standards made from materials rather than chemicals.

* Adapted from AMERICAN WATER WORKS ASSOCIATION. 1993. Flavor Profile Analysis: Screening and Training of Panelists. AWWA Manual. American Water Works Assoc., Denver, Colo.

- AN ERLENMEYER FLASK SHOULD BE USED TO CONTAIN ALL SAMPLES
- EACH ERLENMEYER FLASK SHOULD BE STOPPERED
- THE SAMPLES SHOULD BE WARMED IN A BATH AT 45 °C BEFORE TEST
- EACH SAMPLE SHOULD LABELED WITH AROMA DESCRIPTION AND PRESENTED TO PANELIST FOR MEMORIZATION

- ON COMPLETION OF TASK STOCK SAMPLES SHOULD BE REMOVED FOR SCREENING TEST TO BEGIN

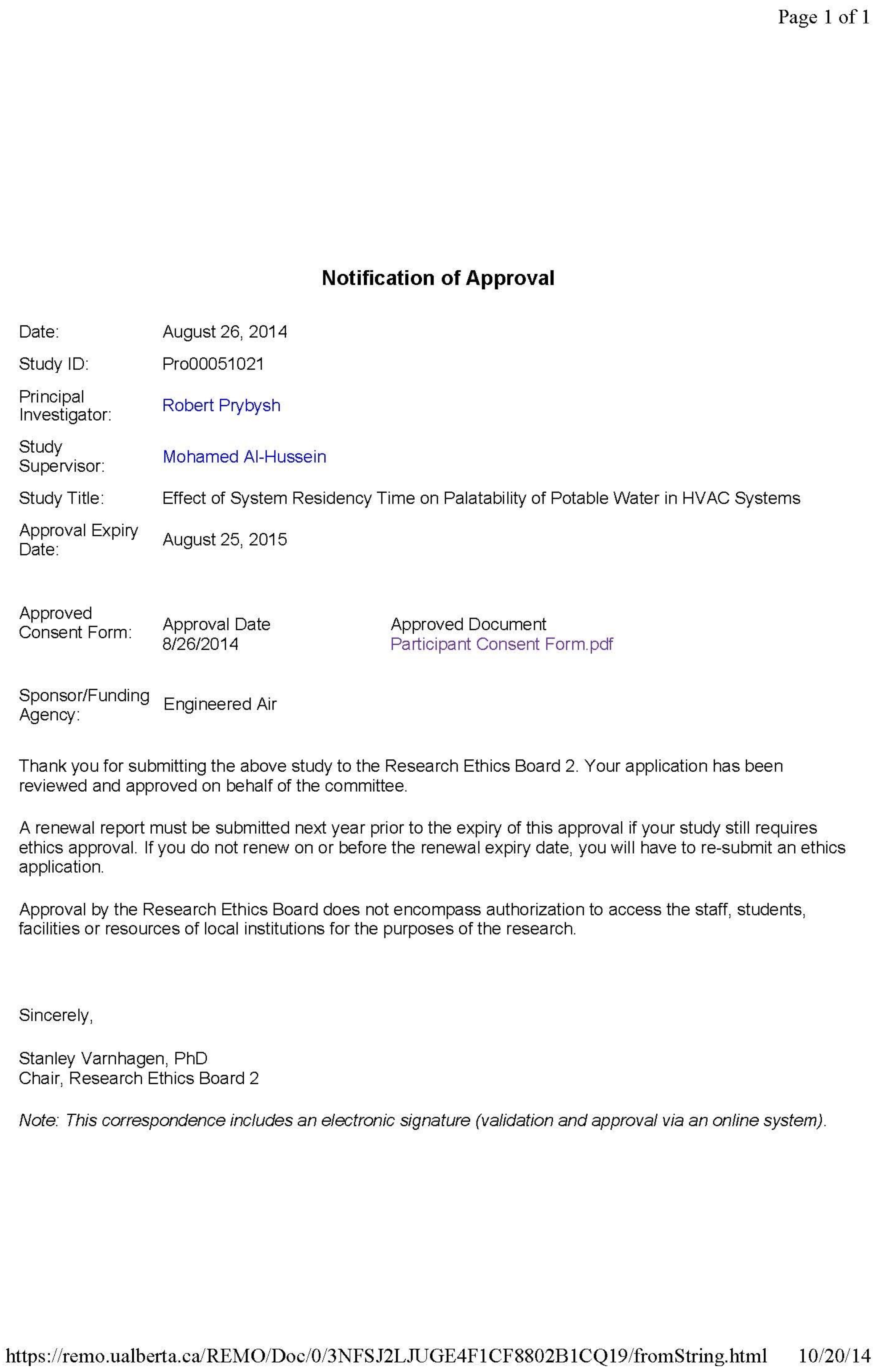
ODOR ANALYSIS

- PREPARE A ROW OF SIX SAMPLES WITHOUT LABELS FOR EACH PANELIST ONE OF EACH STOCK SOLUTION ONE ODOR AND TASTE FREE WATER AND ONE ODOR REPLICATE
- THE SAMPLE KNOWN TO BE THE MOST FATIGUING SHOULD BE PLACED NEAR THE END OF SAMPLE ROW
- AN ODOR RECORD SHEET SHOULD BE PROVIDED TO EACH PANELIST

REFERENCES

1. Bartels, Jeroen HM, Brian M. Brady, and Irwin H. Suffet. "Training panelists for the flavor profile analysis method." *Journal of the American Water Works Association* 79.1 (1987): 26-32.
2. Guidelines For The Selection And Training Of Sensory Panel Members / Sponsored By ASTM Committee E-18 On Sensory Evaluation Of Materials And Products. n.p.: Philadelphia, Pa. (1916 Race St., Philadelphia 19103) : American Society for Testing and Materials, c1981., 1981. NEOS's Catalog. Web. 3 Dec. 2013.
3. American Water Works Association. "Flavor Profile Analysis: Screening and Training of Panelists." *AWWA Manual. American Water Works Assoc., Denver, CO* (1993).

APPENDIX C: University of Alberta Research Ethics Office Notification of Approval



Page 1 of 1

Notification of Approval

Date:	August 26, 2014	
Study ID:	Pro00051021	
Principal Investigator:	Robert Prybysh	
Study Supervisor:	Mohamed Al-Hussein	
Study Title:	Effect of System Residency Time on Palatability of Potable Water in HVAC Systems	
Approval Expiry Date:	August 25, 2015	
Approved Consent Form:	Approval Date 8/26/2014	Approved Document Participant Consent Form.pdf
Sponsor/Funding Agency:	Engineered Air	

Thank you for submitting the above study to the Research Ethics Board 2. Your application has been reviewed and approved on behalf of the committee.

A renewal report must be submitted next year prior to the expiry of this approval if your study still requires ethics approval. If you do not renew on or before the renewal expiry date, you will have to re-submit an ethics application.

Approval by the Research Ethics Board does not encompass authorization to access the staff, students, facilities or resources of local institutions for the purposes of the research.

Sincerely,

Stanley Varnhagen, PhD
Chair, Research Ethics Board 2

Note: This correspondence includes an electronic signature (validation and approval via an online system).

https://remo.ualberta.ca/REMO/Doc/0/3NFSJ2LJUGE4F1CF8802B1CQ19/fromString.html 10/20/14

APPENDIX D: ALS Laboratory Reference Information and Sample QC Data

Reference Information

Sample Parameter Qualifier Key:

Qualifier	Description
DLHC	Detection Limit Raised: Dilution required due to high concentration of test analyte(s).

Test Method References:

ALS Test Code	Matrix	Test Description	Method Reference**
CHLORAMINES-CALC-ED	Water	Total Chlorine minus Free Chlorine	APHA 4500 CL G-COLORIMETRY
CL-IC-N-ED	Water	Chloride in Water by IC	EPA 300.1 (mod)
Inorganic anions are analyzed by Ion Chromatography with conductivity and/or UV detection.			
CL2-FREE-ED	Water	Chlorine, Free	APHA 4500 Cl G-Colorimetry
CL2-TOT-ED	Water	Chlorine, Total	APHA 4500 Cl G-Colorimetry
F-IC-N-ED	Water	Fluoride in Water by IC	EPA 300.1 (mod)
Inorganic anions are analyzed by Ion Chromatography with conductivity and/or UV detection.			
IONBALANCE-ED	Water	Ion Balance Calculation	APHA 1030E
MET-D-CCMS-ED	Water	Dissolved Metals in Water by CRC ICPMS	APHA 3030B/6020A (mod)
Water samples are filtered (0.45 um), preserved with nitric acid, and analyzed by CRC ICPMS. Method Limitation (re: Sulfur): Sulfide and volatile sulfur species may not be recovered by this method.			
NH3-CFA-ED	Water	Ammonia in Water by Colour	APHA 4500 NH3-NITROGEN (AMMONIA)
This analysis is carried out using procedures adapted from APHA Method 4500 NH3 "NITROGEN (AMMONIA)". Ammonia is determined using the automated phenate colourimetric method.			
NO2+NO3-CALC-ED	Water	Nitrate+Nitrite	CALCULATION
NO2-IC-N-ED	Water	Nitrite in Water by IC	EPA 300.1 (mod)
Inorganic anions are analyzed by Ion Chromatography with conductivity and/or UV detection.			
NO3-IC-N-ED	Water	Nitrate in Water by IC	EPA 300.1 (mod)
Inorganic anions are analyzed by Ion Chromatography with conductivity and/or UV detection.			
PH/EC/ALK-ED	Water	pH, Conductivity and Total Alkalinity	APHA 4500-H, 2510, 2320
All samples analyzed by this method for pH will have exceeded the 15 minute recommended hold time from time of sampling (field analysis is recommended for pH where highly accurate results are needed)			
SO4-IC-N-ED	Water	Sulfate in Water by IC	EPA 300.1 (mod)
Inorganic anions are analyzed by Ion Chromatography with conductivity and/or UV detection.			

** ALS test methods may incorporate modifications from specified reference methods to improve performance.

The last two letters of the above test code(s) indicate the laboratory that performed analytical analysis for that test. Refer to the list below:

Laboratory Definition Code	Laboratory Location
ED	ALS ENVIRONMENTAL - EDMONTON, ALBERTA, CANADA

Chain of Custody Numbers:

14-532504

Reference Information

Test Method References:

ALS Test Code	Matrix	Test Description	Method Reference**

GLOSSARY OF REPORT TERMS

Surrogates are compounds that are similar in behaviour to target analyte(s), but that do not normally occur in environmental samples. For applicable tests, surrogates are added to samples prior to analysis as a check on recovery. In reports that display the D.L. column, laboratory objectives for surrogates are listed there.
mg/kg - milligrams per kilogram based on dry weight of sample
mg/kg wwt - milligrams per kilogram based on wet weight of sample
mg/kg lwt - milligrams per kilogram based on lipid-adjusted weight
mg/L - unit of concentration based on volume, parts per million.
< - Less than.
D.L. - The reporting limit.
N/A - Result not available. Refer to qualifier code and definition for explanation.

Test results reported relate only to the samples as received by the laboratory.
UNLESS OTHERWISE STATED, ALL SAMPLES WERE RECEIVED IN ACCEPTABLE CONDITION.
Analytical results in unsigned test reports with the DRAFT watermark are subject to change, pending final QC review.

Quality Control Report

Workorder: L1758747 Report Date: 28-APR-16

Client: UNIVERSITY OF ALBERTA
7-1 Mechanical Eng. Blvd
Edmonton AB N/A
Contact: Robert Prybysh

Test	Matrix	Reference	Result	Qualifier	Units	RPD	Limit	Analyzed
CL-IC-N-ED	Water							
Batch R3443721								
WG2295188-3 DUP		**L1758810-1**						
Chloride (Cl)		20.2	19.3		mg/L	4.3	20	21-APR-16
WG2295188-7 DUP		**L1758835-1**						
Chloride (Cl)		4.06	3.41		mg/L	17	20	22-APR-16
WG2295188-2 LCS								
Chloride (Cl)			102.6		%		90-110	21-APR-16
WG2295188-5 LCS								
Chloride (Cl)			103.0		%		90-110	21-APR-16
WG2295188-9 LCS								
Chloride (Cl)			104.3		%		90-110	22-APR-16
WG2295188-1 MB								
Chloride (Cl)			<0.50		mg/L		0.5	21-APR-16
WG2295188-10 MB								
Chloride (Cl)			<0.50		mg/L		0.5	22-APR-16
WG2295188-6 MB								
Chloride (Cl)			<0.50		mg/L		0.5	21-APR-16
WG2295188-4 MS		**L1758810-1**						
Chloride (Cl)			98.4		%		75-125	21-APR-16
WG2295188-8 MS		**L1758835-1**						
Chloride (Cl)			103.5		%		75-125	22-APR-16
CL2-FREE-ED	Water							
Batch R3443397								
WG2295189-2 DUP		**L1758747-1**						
Chlorine, Free		0.10	0.11		mg/L	11	26	21-APR-16
WG2295189-1 LCS								
Chlorine, Free			92.7		%		75-125	21-APR-16
CL2-TOT-ED	Water							
Batch R3443395								
WG2295184-2 DUP		**L1758747-1**						
Chlorine, Total		0.13	0.15		mg/L	9.4	10	21-APR-16
WG2295184-1 LCS								
Chlorine, Total			96.3		%		75-125	21-APR-16
F-IC-N-ED	Water							
Batch R3443721								
WG2295188-3 DUP		**L1758810-1**						
Fluoride (F)		0.112	0.111		mg/L	0.5	20	21-APR-16
WG2295188-7 DUP		**L1758835-1**						

Quality Control Report

Workorder: L1758747 Report Date: 28-APR-16

Client: UNIVERSITY OF ALBERTA
7-1 Mechanical Eng. Blvd
Edmonton AB N/A

Contact: Robert Prybysh

Test	Matrix	Reference	Result	Qualifier	Units	RPD	Limit	Analyzed
F-IC-N-ED	Water							
Batch R3443721								
WG2295188-7 DUP		**L1758835-1**						
Fluoride (F)		0.076	0.071		mg/L	7.5	20	22-APR-16
WG2295188-2 LCS								
Fluoride (F)			99.2		%		90-110	21-APR-16
WG2295188-5 LCS								
Fluoride (F)			103.8		%		90-110	21-APR-16
WG2295188-9 LCS								
Fluoride (F)			106.0		%		90-110	22-APR-16
WG2295188-1 MB								
Fluoride (F)			<0.020		mg/L		0.02	21-APR-16
WG2295188-10 MB								
Fluoride (F)			<0.020		mg/L		0.02	22-APR-16
WG2295188-6 MB								
Fluoride (F)			<0.020		mg/L		0.02	21-APR-16
WG2295188-4 MS		**L1758810-1**						
Fluoride (F)			102.7		%		75-125	21-APR-16
WG2295188-8 MS		**L1758835-1**						
Fluoride (F)			102.6		%		75-125	22-APR-16
MET-D-CCMS-ED	Water							
Batch R3444594								
WG2296349-2 CRM		**ED-HIGH-WATRM**						
Aluminum (Al)-Dissolved			100.9		%		80-120	25-APR-16
Antimony (Sb)-Dissolved			101.2		%		80-120	25-APR-16
Arsenic (As)-Dissolved			104.6		%		80-120	25-APR-16
Barium (Ba)-Dissolved			101.9		%		80-120	25-APR-16
Beryllium (Be)-Dissolved			100.2		%		80-120	25-APR-16
Bismuth (Bi)-Dissolved			101.2		%		80-120	25-APR-16
Boron (B)-Dissolved			101.4		%		80-120	25-APR-16
Cadmium (Cd)-Dissolved			97.4		%		80-120	25-APR-16
Calcium (Ca)-Dissolved			103.0		%		80-120	25-APR-16
Cesium (Cs)-Dissolved			98.3		%		80-120	25-APR-16
Chromium (Cr)-Dissolved			99.5		%		80-120	25-APR-16
Cobalt (Co)-Dissolved			99.8		%		80-120	25-APR-16
Copper (Cu)-Dissolved			99.6		%		80-120	25-APR-16
Iron (Fe)-Dissolved			92.0		%		80-120	25-APR-16
Lead (Pb)-Dissolved			101.5		%		80-120	25-APR-16

Quality Control Report

Workorder: L1758747 Report Date: 28-APR-16

Client: UNIVERSITY OF ALBERTA
7-1 Mechanical Eng. Blvd
Edmonton AB N/A
Contact: Robert Prybysh

Test	Matrix	Reference	Result	Qualifier	Units	RPD	Limit	Analyzed
MET-D-CCMS-ED	Water							
Batch R3444594								
WG2296349-2 CRM		**ED-HIGH-WATRM**						
Lithium (Li)-Dissolved			98.0		%		80-120	25-APR-16
Magnesium (Mg)-Dissolved			101.6		%		80-120	25-APR-16
Manganese (Mn)-Dissolved			103.8		%		80-120	25-APR-16
Molybdenum (Mo)-Dissolved			102.4		%		80-120	25-APR-16
Nickel (Ni)-Dissolved			102.0		%		80-120	25-APR-16
Phosphorus (P)-Dissolved			97.6		%		80-120	25-APR-16
Potassium (K)-Dissolved			99.0		%		80-120	25-APR-16
Rubidium (Rb)-Dissolved			103.4		%		80-120	25-APR-16
Selenium (Se)-Dissolved			97.1		%		80-120	25-APR-16
Silicon (Si)-Dissolved			109.9		%		80-120	25-APR-16
Silver (Ag)-Dissolved			104.2		%		80-120	25-APR-16
Sodium (Na)-Dissolved			97.8		%		80-120	25-APR-16
Strontium (Sr)-Dissolved			103.3		%		80-120	25-APR-16
Sulfur (S)-Dissolved			101.3		%		80-120	25-APR-16
Tellurium (Te)-Dissolved			103.9		%		80-120	25-APR-16
Thallium (Tl)-Dissolved			100.9		%		80-120	25-APR-16
Thorium (Th)-Dissolved			96.2		%		80-120	25-APR-16
Tin (Sn)-Dissolved			96.3		%		80-120	25-APR-16
Titanium (Ti)-Dissolved			100.2		%		80-120	25-APR-16
Tungsten (W)-Dissolved			103.6		%		80-120	25-APR-16
Uranium (U)-Dissolved			103.7		%		80-120	25-APR-16
Vanadium (V)-Dissolved			101.1		%		80-120	25-APR-16
Zinc (Zn)-Dissolved			96.0		%		80-120	25-APR-16
Zirconium (Zr)-Dissolved			98.6		%		80-120	25-APR-16
WG2296351-2 CRM		**ED-HIGH-WATRM**						
Aluminum (Al)-Dissolved			101.9		%		80-120	25-APR-16
Antimony (Sb)-Dissolved			99.8		%		80-120	25-APR-16
Arsenic (As)-Dissolved			100.4		%		80-120	25-APR-16
Barium (Ba)-Dissolved			105.1		%		80-120	25-APR-16
Beryllium (Be)-Dissolved			98.3		%		80-120	25-APR-16
Bismuth (Bi)-Dissolved			100.1		%		80-120	25-APR-16
Boron (B)-Dissolved			98.3		%		80-120	25-APR-16
Cadmium (Cd)-Dissolved			93.9		%		80-120	25-APR-16
Calcium (Ca)-Dissolved			98.3		%		80-120	25-APR-16

Quality Control Report

Workorder: L1758747 Report Date: 28-APR-16 Page 4 of 16

Client: UNIVERSITY OF ALBERTA
7-1 Mechanical Eng. Blvd
Edmonton AB N/A
Contact: Robert Prybysh

Test	Matrix	Reference	Result	Qualifier	Units	RPD	Limit	Analyzed
MET-D-CCMS-ED	Water							
Batch R3444594								
WG2296351-2 CRM		**ED-HIGH-WATRM**						
Cesium (Cs)-Dissolved			102.9		%		80-120	25-APR-16
Chromium (Cr)-Dissolved			96.1		%		80-120	25-APR-16
Cobalt (Co)-Dissolved			98.1		%		80-120	25-APR-16
Copper (Cu)-Dissolved			97.1		%		80-120	25-APR-16
Iron (Fe)-Dissolved			92.8		%		80-120	25-APR-16
Lead (Pb)-Dissolved			99.6		%		80-120	25-APR-16
Lithium (Li)-Dissolved			97.3		%		80-120	25-APR-16
Magnesium (Mg)-Dissolved			102.2		%		80-120	25-APR-16
Manganese (Mn)-Dissolved			100.4		%		80-120	25-APR-16
Molybdenum (Mo)-Dissolved			100.9		%		80-120	25-APR-16
Nickel (Ni)-Dissolved			99.1		%		80-120	25-APR-16
Phosphorus (P)-Dissolved			100.1		%		80-120	25-APR-16
Potassium (K)-Dissolved			100.9		%		80-120	25-APR-16
Rubidium (Rb)-Dissolved			103.4		%		80-120	25-APR-16
Selenium (Se)-Dissolved			96.7		%		80-120	25-APR-16
Silicon (Si)-Dissolved			114.1		%		80-120	25-APR-16
Silver (Ag)-Dissolved			104.7		%		80-120	25-APR-16
Sodium (Na)-Dissolved			96.5		%		80-120	25-APR-16
Strontium (Sr)-Dissolved			101.6		%		80-120	25-APR-16
Sulfur (S)-Dissolved			103.1		%		80-120	25-APR-16
Tellurium (Te)-Dissolved			100.0		%		80-120	25-APR-16
Thallium (Tl)-Dissolved			99.0		%		80-120	25-APR-16
Thorium (Th)-Dissolved			92.9		%		80-120	25-APR-16
Tin (Sn)-Dissolved			95.8		%		80-120	25-APR-16
Titanium (Ti)-Dissolved			98.1		%		80-120	25-APR-16
Tungsten (W)-Dissolved			100.2		%		80-120	25-APR-16
Uranium (U)-Dissolved			98.4		%		80-120	25-APR-16
Vanadium (V)-Dissolved			99.1		%		80-120	25-APR-16
Zinc (Zn)-Dissolved			94.4		%		80-120	25-APR-16
Zirconium (Zr)-Dissolved			97.1		%		80-120	25-APR-16
WG2296349-3 DUP		**L1758747-1**						
Aluminum (Al)-Dissolved		0.0764	0.0758		mg/L	0.8	20	25-APR-16
Antimony (Sb)-Dissolved		<0.00010	<0.00010	RPD-NA	mg/L	N/A	20	25-APR-16
Arsenic (As)-Dissolved		0.00012	0.00011		mg/L			25-APR-16

Quality Control Report

Workorder: L1758747 Report Date: 28-APR-16

Client: UNIVERSITY OF ALBERTA
7-1 Mechanical Eng. Blvd
Edmonton AB N/A

Contact: Robert Prybysh

Test	Matrix	Reference	Result	Qualifier	Units	RPD	Limit	Analyzed
MET-D-CCMS-ED	Water							
Batch **R3444594**								
WG2296349-3 DUP		**L1758747-1**						
Arsenic (As)-Dissolved		0.00012	0.00011		mg/L	9.0	20	25-APR-16
Barium (Ba)-Dissolved		0.0507	0.0516		mg/L	1.6	20	25-APR-16
Beryllium (Be)-Dissolved		<0.00010	<0.00010	RPD-NA	mg/L	N/A	20	25-APR-16
Bismuth (Bi)-Dissolved		<0.000050	<0.000050	RPD-NA	mg/L	N/A	20	25-APR-16
Boron (B)-Dissolved		<0.010	<0.010	RPD-NA	mg/L	N/A	20	25-APR-16
Cadmium (Cd)-Dissolved		0.0000071	0.0000063		mg/L	13	20	25-APR-16
Calcium (Ca)-Dissolved		47.3	46.7		mg/L	1.1	20	25-APR-16
Cesium (Cs)-Dissolved		<0.000010	<0.000010	RPD-NA	mg/L	N/A	20	25-APR-16
Chromium (Cr)-Dissolved		0.00015	0.00013		mg/L	13	20	25-APR-16
Cobalt (Co)-Dissolved		<0.00010	<0.00010	RPD-NA	mg/L	N/A	20	25-APR-16
Copper (Cu)-Dissolved		0.101	0.101		mg/L	0.1	20	25-APR-16
Iron (Fe)-Dissolved		<0.010	<0.010	RPD-NA	mg/L	N/A	20	25-APR-16
Lead (Pb)-Dissolved		0.000687	0.000705		mg/L	2.5	20	25-APR-16
Lithium (Li)-Dissolved		0.0029	0.0028		mg/L	4.3	20	25-APR-16
Magnesium (Mg)-Dissolved		13.2	13.0		mg/L	1.4	20	25-APR-16
Manganese (Mn)-Dissolved		0.00054	0.00053		mg/L	0.5	20	25-APR-16
Molybdenum (Mo)-Dissolved		0.000675	0.000673		mg/L	0.3	20	25-APR-16
Nickel (Ni)-Dissolved		0.0107	0.0107		mg/L	0.4	20	25-APR-16
Phosphorus (P)-Dissolved		<0.050	<0.050	RPD-NA	mg/L	N/A	20	25-APR-16
Potassium (K)-Dissolved		0.88	0.88		mg/L	0.7	20	25-APR-16
Rubidium (Rb)-Dissolved		0.00030	0.00027		mg/L	9.7	20	25-APR-16
Selenium (Se)-Dissolved		0.000276	0.000266		mg/L	3.5	20	25-APR-16
Silicon (Si)-Dissolved		1.75	1.73		mg/L	0.7	20	25-APR-16
Silver (Ag)-Dissolved		<0.000010	<0.000010	RPD-NA	mg/L	N/A	20	25-APR-16
Sodium (Na)-Dissolved		8.4	8.7		mg/L	3.1	20	25-APR-16
Strontium (Sr)-Dissolved		0.416	0.406		mg/L	2.5	20	25-APR-16
Sulfur (S)-Dissolved		23.6	23.5		mg/L	0.4	20	25-APR-16
Tellurium (Te)-Dissolved		<0.00020	<0.00020	RPD-NA	mg/L	N/A	20	25-APR-16
Thallium (Tl)-Dissolved		<0.000010	<0.000010	RPD-NA	mg/L	N/A	20	25-APR-16
Thorium (Th)-Dissolved		<0.00010	<0.00010	RPD-NA	mg/L	N/A	20	25-APR-16
Tin (Sn)-Dissolved		<0.00010	<0.00010	RPD-NA	mg/L	N/A	20	25-APR-16
Titanium (Ti)-Dissolved		<0.00030	<0.00030	RPD-NA	mg/L	N/A	20	25-APR-16
Tungsten (W)-Dissolved		<0.00010	<0.00010		mg/L			25-APR-16

Quality Control Report

Client: UNIVERSITY OF ALBERTA
7-1 Mechanical Eng. Blvd
Edmonton AB N/A
Contact: Robert Prybysh

Test	Matrix	Reference	Result	Qualifier	Units	RPD	Limit	Analyzed
MET-D-CCMS-ED	Water							
Batch R3444594								
WG2296349-3 DUP		**L1758747-1**						
Tungsten (W)-Dissolved		<0.00010	<0.00010	RPD-NA	mg/L	N/A	20	25-APR-16
Uranium (U)-Dissolved		0.000232	0.000237		mg/L	2.5	20	25-APR-16
Vanadium (V)-Dissolved		<0.00050	<0.00050	RPD-NA	mg/L	N/A	20	25-APR-16
Zinc (Zn)-Dissolved		0.0112	0.0110		mg/L	1.6	20	25-APR-16
Zirconium (Zr)-Dissolved		<0.00030	<0.00030	RPD-NA	mg/L	N/A	20	25-APR-16
WG2296351-3 DUP		**L1758793-8**						
Aluminum (Al)-Dissolved		<0.0010	<0.0010	RPD-NA	mg/L	N/A	20	25-APR-16
Antimony (Sb)-Dissolved		<0.00010	<0.00010	RPD-NA	mg/L	N/A	20	25-APR-16
Arsenic (As)-Dissolved		<0.00010	<0.00010	RPD-NA	mg/L	N/A	20	25-APR-16
Barium (Ba)-Dissolved		<0.000050	<0.000050	RPD-NA	mg/L	N/A	20	25-APR-16
Beryllium (Be)-Dissolved		<0.00010	<0.00010	RPD-NA	mg/L	N/A	20	25-APR-16
Bismuth (Bi)-Dissolved		<0.000050	<0.000050	RPD-NA	mg/L	N/A	20	25-APR-16
Boron (B)-Dissolved		<0.010	<0.010	RPD-NA	mg/L	N/A	20	25-APR-16
Cadmium (Cd)-Dissolved		<0.0000050	<0.000005	RPD-NA	mg/L	N/A	20	25-APR-16
Calcium (Ca)-Dissolved		<0.050	<0.050	RPD-NA	mg/L	N/A	20	25-APR-16
Cesium (Cs)-Dissolved		<0.000010	<0.000010	RPD-NA	mg/L	N/A	20	25-APR-16
Chromium (Cr)-Dissolved		<0.00010	<0.00010	RPD-NA	mg/L	N/A	20	25-APR-16
Cobalt (Co)-Dissolved		<0.00010	<0.00010	RPD-NA	mg/L	N/A	20	25-APR-16
Copper (Cu)-Dissolved		<0.00020	<0.00020	RPD-NA	mg/L	N/A	20	25-APR-16
Iron (Fe)-Dissolved		<0.010	<0.010	RPD-NA	mg/L	N/A	20	25-APR-16
Lead (Pb)-Dissolved		<0.000050	<0.000050	RPD-NA	mg/L	N/A	20	25-APR-16
Lithium (Li)-Dissolved		<0.0010	<0.0010	RPD-NA	mg/L	N/A	20	25-APR-16
Magnesium (Mg)-Dissolved		<0.0050	<0.0050	RPD-NA	mg/L	N/A	20	25-APR-16
Manganese (Mn)-Dissolved		<0.00010	<0.00010	RPD-NA	mg/L	N/A	20	25-APR-16
Molybdenum (Mo)-Dissolved		<0.000050	<0.000050	RPD-NA	mg/L	N/A	20	25-APR-16
Nickel (Ni)-Dissolved		<0.00050	<0.00050	RPD-NA	mg/L	N/A	20	25-APR-16
Phosphorus (P)-Dissolved		<0.050	<0.050	RPD-NA	mg/L	N/A	20	25-APR-16
Potassium (K)-Dissolved		<0.050	<0.050	RPD-NA	mg/L	N/A	20	25-APR-16
Rubidium (Rb)-Dissolved		<0.00020	<0.00020	RPD-NA	mg/L	N/A	20	25-APR-16
Selenium (Se)-Dissolved		<0.000050	<0.000050	RPD-NA	mg/L	N/A	20	25-APR-16
Silicon (Si)-Dissolved		<0.050	<0.050	RPD-NA	mg/L	N/A	20	25-APR-16
Silver (Ag)-Dissolved		<0.000010	<0.000010	RPD-NA	mg/L	N/A	20	25-APR-16
Sodium (Na)-Dissolved		<0.050	<0.050	RPD-NA	mg/L	N/A	20	25-APR-16

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Contact: Robert Prybysh

Test	Matrix	Reference	Result	Qualifier	Units	RPD	Limit	Analyzed
MET-D-CCMS-ED	Water							
Batch R3444594								
WG2296351-3 DUP		**L1758793-8**						
Strontium (Sr)-Dissolved		<0.00020	<0.00020	RPD-NA	mg/L	N/A	20	25-APR-16
Sulfur (S)-Dissolved		<0.50	<0.50	RPD-NA	mg/L	N/A	20	25-APR-16
Tellurium (Te)-Dissolved		<0.00020	<0.00020	RPD-NA	mg/L	N/A	20	25-APR-16
Thallium (Tl)-Dissolved		<0.000010	<0.000010	RPD-NA	mg/L	N/A	20	25-APR-16
Thorium (Th)-Dissolved		<0.00010	<0.00010	RPD-NA	mg/L	N/A	20	25-APR-16
Tin (Sn)-Dissolved		<0.00010	<0.00010	RPD-NA	mg/L	N/A	20	25-APR-16
Titanium (Ti)-Dissolved		<0.00030	<0.00030	RPD-NA	mg/L	N/A	20	25-APR-16
Tungsten (W)-Dissolved		<0.00010	<0.00010	RPD-NA	mg/L	N/A	20	25-APR-16
Uranium (U)-Dissolved		<0.000010	<0.000010	RPD-NA	mg/L	N/A	20	25-APR-16
Vanadium (V)-Dissolved		<0.00050	<0.00050	RPD-NA	mg/L	N/A	20	25-APR-16
Zinc (Zn)-Dissolved		<0.0010	<0.0010	RPD-NA	mg/L	N/A	20	25-APR-16
Zirconium (Zr)-Dissolved		<0.00030	<0.00030	RPD-NA	mg/L	N/A	20	25-APR-16
WG2296349-1 MB								
Aluminum (Al)-Dissolved			<0.0010		mg/L		0.001	25-APR-16
Antimony (Sb)-Dissolved			<0.00010		mg/L		0.0001	25-APR-16
Arsenic (As)-Dissolved			<0.00010		mg/L		0.0001	25-APR-16
Barium (Ba)-Dissolved			<0.000050		mg/L		0.00005	25-APR-16
Beryllium (Be)-Dissolved			<0.00010		mg/L		0.0001	25-APR-16
Bismuth (Bi)-Dissolved			<0.000050		mg/L		0.00005	25-APR-16
Boron (B)-Dissolved			<0.010		mg/L		0.01	25-APR-16
Cadmium (Cd)-Dissolved			<0.000005		mg/L		0.000005	25-APR-16
Calcium (Ca)-Dissolved			<0.050		mg/L		0.05	25-APR-16
Cesium (Cs)-Dissolved			<0.000010		mg/L		0.00001	25-APR-16
Chromium (Cr)-Dissolved			<0.00010		mg/L		0.0001	25-APR-16
Cobalt (Co)-Dissolved			<0.00010		mg/L		0.0001	25-APR-16
Copper (Cu)-Dissolved			<0.00020		mg/L		0.0002	25-APR-16
Iron (Fe)-Dissolved			<0.010		mg/L		0.01	25-APR-16
Lead (Pb)-Dissolved			<0.000050		mg/L		0.00005	25-APR-16
Lithium (Li)-Dissolved			<0.0010		mg/L		0.001	25-APR-16
Magnesium (Mg)-Dissolved			<0.0050		mg/L		0.005	25-APR-16
Manganese (Mn)-Dissolved			<0.00010		mg/L		0.0001	25-APR-16
Molybdenum (Mo)-Dissolved			<0.000050		mg/L		0.00005	25-APR-16
Nickel (Ni)-Dissolved			<0.00050		mg/L		0.0005	25-APR-16

Quality Control Report

Workorder: L1758747 Report Date: 28-APR-16

Client: UNIVERSITY OF ALBERTA
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Test	Matrix	Reference	Result	Qualifier	Units	RPD	Limit	Analyzed
MET-D-CCMS-ED	Water							
Batch R3444594								
WG2296349-1 MB								
Phosphorus (P)-Dissolved			<0.050		mg/L		0.05	25-APR-16
Potassium (K)-Dissolved			<0.050		mg/L		0.05	25-APR-16
Rubidium (Rb)-Dissolved			<0.00020		mg/L		0.0002	25-APR-16
Selenium (Se)-Dissolved			<0.000050		mg/L		0.00005	25-APR-16
Silicon (Si)-Dissolved			<0.050		mg/L		0.05	25-APR-16
Silver (Ag)-Dissolved			<0.000010		mg/L		0.00001	25-APR-16
Sodium (Na)-Dissolved			<0.050		mg/L		0.05	25-APR-16
Strontium (Sr)-Dissolved			<0.00020		mg/L		0.0002	25-APR-16
Sulfur (S)-Dissolved			<0.50		mg/L		0.5	25-APR-16
Tellurium (Te)-Dissolved			<0.00020		mg/L		0.0002	25-APR-16
Thallium (Tl)-Dissolved			<0.000010		mg/L		0.00001	25-APR-16
Thorium (Th)-Dissolved			<0.00010		mg/L		0.0001	25-APR-16
Tin (Sn)-Dissolved			<0.00010		mg/L		0.0001	25-APR-16
Titanium (Ti)-Dissolved			<0.00030		mg/L		0.0003	25-APR-16
Tungsten (W)-Dissolved			<0.00010		mg/L		0.0001	25-APR-16
Uranium (U)-Dissolved			<0.000010		mg/L		0.00001	25-APR-16
Vanadium (V)-Dissolved			<0.00050		mg/L		0.0005	25-APR-16
Zinc (Zn)-Dissolved			<0.0010		mg/L		0.001	25-APR-16
Zirconium (Zr)-Dissolved			<0.00030		mg/L		0.0003	25-APR-16
NH3-CFA-ED	Water							
Batch R3444122								
WG2296646-3 DUP		**L1759540-3**						
Ammonia, Total (as N)		<0.050	<0.050	RPD-NA	mg/L	N/A	20	25-APR-16
WG2296646-7 DUP		**L1757192-4**						
Ammonia, Total (as N)		1.51	1.47		mg/L	2.6	20	25-APR-16
WG2296646-2 LCS								
Ammonia, Total (as N)			103.3		%		85-115	25-APR-16
WG2296646-6 LCS								
Ammonia, Total (as N)			103.7		%		85-115	25-APR-16
WG2296646-1 MB								
Ammonia, Total (as N)			<0.050		mg/L		0.05	25-APR-16
WG2296646-5 MB								
Ammonia, Total (as N)			<0.050		mg/L		0.05	25-APR-16
WG2296646-4 MS		**L1759540-3**						
Ammonia, Total (as N)			98.8		%		75-125	25-APR-16

Quality Control Report

Client: UNIVERSITY OF ALBERTA
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Test	Matrix	Reference	Result	Qualifier	Units	RPD	Limit	Analyzed
NH3-CFA-ED	Water							
Batch R3444122								
WG2296646-8 MS		**L1757192-3**						
Ammonia, Total (as N)			100.5		%		75-125	25-APR-16
Batch R3446964								
WG2298534-3 DUP		**L1758747-10**						
Ammonia, Total (as N)		0.448	0.472		mg/L	5.3	20	27-APR-16
WG2298534-5 DUP		**L1758865-1**						
Ammonia, Total (as N)		0.370	0.358		mg/L	3.4	20	27-APR-16
WG2298534-2 LCS								
Ammonia, Total (as N)			100.0		%		85-115	27-APR-16
WG2298534-8 LCS								
Ammonia, Total (as N)			108.0		%		85-115	27-APR-16
WG2298534-1 MB								
Ammonia, Total (as N)			<0.050		mg/L		0.05	27-APR-16
WG2298534-7 MB								
Ammonia, Total (as N)			<0.050		mg/L		0.05	27-APR-16
WG2298534-4 MS		**L1758747-10**						
Ammonia, Total (as N)			106.0		%		75-125	27-APR-16
WG2298534-6 MS		**L1758865-1**						
Ammonia, Total (as N)			119.0		%		75-125	27-APR-16
NO2-IC-N-ED	Water							
Batch R3443721								
WG2295188-3 DUP		**L1758810-1**						
Nitrite (as N)		<0.010	<0.010	RPD-NA	mg/L	N/A	20	21-APR-16
WG2295188-7 DUP		**L1758835-1**						
Nitrite (as N)		<0.010	<0.010	RPD-NA	mg/L	N/A	20	22-APR-16
WG2295188-2 LCS								
Nitrite (as N)			104.4		%		90-110	21-APR-16
WG2295188-5 LCS								
Nitrite (as N)			102.1		%		90-110	21-APR-16
WG2295188-9 LCS								
Nitrite (as N)			104.4		%		90-110	22-APR-16
WG2295188-1 MB								
Nitrite (as N)			<0.010		mg/L		0.01	21-APR-16
WG2295188-10 MB								
Nitrite (as N)			<0.010		mg/L		0.01	22-APR-16
WG2295188-6 MB								
Nitrite (as N)			<0.010		mg/L		0.01	21-APR-16

Test	Matrix	Reference	Result	Qualifier	Units	RPD	Limit	Analyzed
NO2-IC-N-ED	Water							
Batch R3443721								
WG2295188-4 MS		**L1758810-1**						
Nitrite (as N)			95.5		%		75-125	21-APR-16
WG2295188-8 MS		**L1758835-1**						
Nitrite (as N)			96.7		%		75-125	22-APR-16
NO3-IC-N-ED	Water							
Batch R3443721								
WG2295188-3 DUP		**L1758810-1**						
Nitrate (as N)		<0.020	<0.020	RPD-NA	mg/L	N/A	20	21-APR-16
WG2295188-7 DUP		**L1758835-1**						
Nitrate (as N)		0.262	0.232		mg/L	12	20	22-APR-16
WG2295188-2 LCS								
Nitrate (as N)			99.9		%		90-110	21-APR-16
WG2295188-5 LCS								
Nitrate (as N)			99.6		%		90-110	21-APR-16
WG2295188-9 LCS								
Nitrate (as N)			101.7		%		90-110	22-APR-16
WG2295188-1 MB								
Nitrate (as N)			<0.020		mg/L		0.02	21-APR-16
WG2295188-10 MB								
Nitrate (as N)			<0.020		mg/L		0.02	22-APR-16
WG2295188-6 MB								
Nitrate (as N)			<0.020		mg/L		0.02	21-APR-16
WG2295188-4 MS		**L1758810-1**						
Nitrate (as N)			96.2		%		75-125	21-APR-16
WG2295188-8 MS		**L1758835-1**						
Nitrate (as N)			100.3		%		75-125	22-APR-16
PH/EC/ALK-ED	Water							
Batch R3443166								
WG2295401-6 DUP		**L1758793-4**						
pH		7.62	7.63	J	pH	0.01	0.3	22-APR-16
Conductivity (EC)		6750	6660		uS/cm	1.4	10	22-APR-16
Bicarbonate (HCO3)		1800	1810		mg/L	0.7	25	22-APR-16
Carbonate (CO3)		<5.0	<5.0	RPD-NA	mg/L	N/A	25	22-APR-16
Hydroxide (OH)		<5.0	<5.0	RPD-NA	mg/L	N/A	25	22-APR-16
Alkalinity, Total (as CaCO3)		1470	1480		mg/L	0.7	20	22-APR-16
WG2295401-9 DUP		**L1759032-11**						
pH		7.69	7.68	J	pH	0.01	0.3	22-APR-16

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Test	Matrix	Reference	Result	Qualifier	Units	RPD	Limit	Analyzed
PH/EC/ALK-ED	Water							
Batch R3443166								
WG2295401-9 DUP		**L1759032-11**						
Conductivity (EC)		1250	1260		uS/cm	0.4	10	22-APR-16
Bicarbonate (HCO3)		752	763		mg/L	1.5	25	22-APR-16
Carbonate (CO3)		<5.0	<5.0	RPD-NA	mg/L	N/A	25	22-APR-16
Hydroxide (OH)		<5.0	<5.0	RPD-NA	mg/L	N/A	25	22-APR-16
Alkalinity, Total (as CaCO3)		617	626		mg/L	1.5	20	22-APR-16
WG2295401-11 LCS								
Conductivity (EC)			99.9		%		90-110	22-APR-16
WG2295401-12 LCS								
pH			6.03		pH		5.9-6.1	22-APR-16
WG2295401-13 LCS								
Alkalinity, Total (as CaCO3)			98.1		%		85-115	22-APR-16
WG2295401-14 LCS								
Conductivity (EC)			99.0		%		90-110	22-APR-16
WG2295401-16 LCS								
Conductivity (EC)			98.6		%		90-110	22-APR-16
WG2295401-17 LCS								
pH			6.03		pH		5.9-6.1	22-APR-16
WG2295401-18 LCS								
Alkalinity, Total (as CaCO3)			99.8		%		85-115	22-APR-16
WG2295401-19 LCS								
Conductivity (EC)			97.7		%		90-110	22-APR-16
WG2295401-2 LCS								
Conductivity (EC)			101.5		%		90-110	22-APR-16
WG2295401-21 LCS								
Conductivity (EC)			96.8		%		90-110	22-APR-16
WG2295401-22 LCS								
pH			6.03		pH		5.9-6.1	22-APR-16
WG2295401-23 LCS								
Alkalinity, Total (as CaCO3)			100.6		%		85-115	22-APR-16
WG2295401-24 LCS								
Conductivity (EC)			93.9		%		90-110	22-APR-16
WG2295401-3 LCS								
pH			6.03		pH		5.9-6.1	22-APR-16
WG2295401-4 LCS								
Alkalinity, Total (as CaCO3)			96.9		%		85-115	22-APR-16
WG2295401-5 LCS								
Conductivity (EC)			100.4		%		90-110	22-APR-16

Client: UNIVERSITY OF ALBERTA
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Test	Matrix	Reference	Result	Qualifier	Units	RPD	Limit	Analyzed
PH/EC/ALK-ED	Water							
Batch R3443166								
WG2295401-1 MB								
Bicarbonate (HCO3)			<5.0		mg/L		5	22-APR-16
Carbonate (CO3)			<5.0		mg/L		5	22-APR-16
Hydroxide (OH)			<5.0		mg/L		5	22-APR-16
Alkalinity, Total (as CaCO3)			<2.0		mg/L		2	22-APR-16
WG2295401-10 MB								
Bicarbonate (HCO3)			<5.0		mg/L		5	22-APR-16
Carbonate (CO3)			<5.0		mg/L		5	22-APR-16
Hydroxide (OH)			<5.0		mg/L		5	22-APR-16
Alkalinity, Total (as CaCO3)			<2.0		mg/L		2	22-APR-16
WG2295401-15 MB								
Bicarbonate (HCO3)			<5.0		mg/L		5	22-APR-16
Carbonate (CO3)			<5.0		mg/L		5	22-APR-16
Hydroxide (OH)			<5.0		mg/L		5	22-APR-16
Alkalinity, Total (as CaCO3)			<2.0		mg/L		2	22-APR-16
WG2295401-20 MB								
Bicarbonate (HCO3)			<5.0		mg/L		5	22-APR-16
Carbonate (CO3)			<5.0		mg/L		5	22-APR-16
Hydroxide (OH)			<5.0		mg/L		5	22-APR-16
Alkalinity, Total (as CaCO3)			<2.0		mg/L		2	22-APR-16
SO4-IC-N-ED	Water							
Batch R3443721								
WG2295188-3 DUP		**L1758810-1**						
Sulfate (SO4)		7.45	7.42		mg/L	0.5	20	21-APR-16
WG2295188-7 DUP		**L1758835-1**						
Sulfate (SO4)		91.2	90.3		mg/L	1.0	20	22-APR-16
WG2295188-2 LCS								
Sulfate (SO4)			102.7		%		90-110	21-APR-16
WG2295188-5 LCS								
Sulfate (SO4)			102.8		%		90-110	21-APR-16
WG2295188-9 LCS								
Sulfate (SO4)			103.9		%		90-110	22-APR-16
WG2295188-1 MB								
Sulfate (SO4)			<0.30		mg/L		0.3	21-APR-16
WG2295188-10 MB								
Sulfate (SO4)			<0.30		mg/L		0.3	22-APR-16
WG2295188-6 MB								

Test	Matrix	Reference	Result	Qualifier	Units	RPD	Limit	Analyzed
SO4-IC-N-ED	Water							
Batch R3443721								
WG2295188-6 MB								
Sulfate (SO4)			<0.30		mg/L		0.3	21-APR-16
WG2295188-4 MS		**L1758810-1**						
Sulfate (SO4)			99.3		%		75-125	21-APR-16
WG2295188-8 MS		**L1758835-1**						
Sulfate (SO4)			92.6		%		75-125	22-APR-16

Quality Control Report

Workorder: L1758747 Report Date: 28-APR-16

Client: UNIVERSITY OF ALBERTA
7-1 Mechanical Eng. Blvd
Edmonton AB N/A
Contact: Robert Prybysh

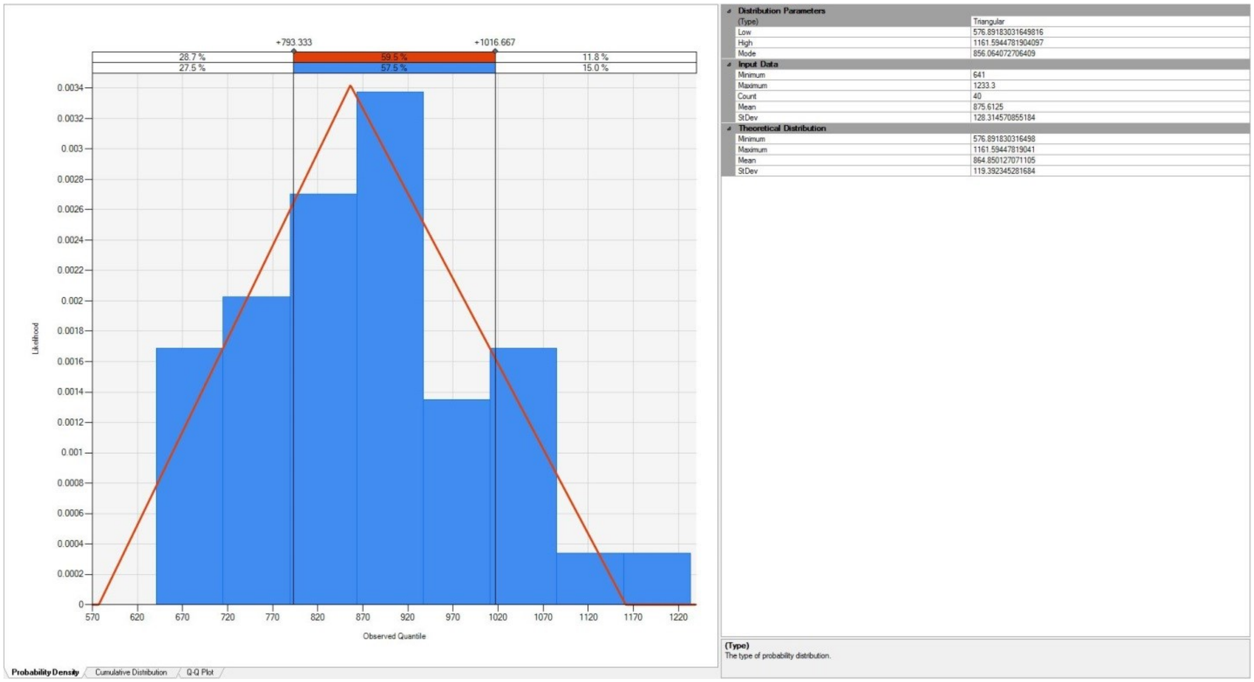
Legend:

Limit	ALS Control Limit (Data Quality Objectives)
DUP	Duplicate
RPD	Relative Percent Difference
N/A	Not Available
LCS	Laboratory Control Sample
SRM	Standard Reference Material
MS	Matrix Spike
MSD	Matrix Spike Duplicate
ADE	Average Desorption Efficiency
MB	Method Blank
IRM	Internal Reference Material
CRM	Certified Reference Material
CCV	Continuing Calibration Verification
CVS	Calibration Verification Standard
LCSD	Laboratory Control Sample Duplicate

Sample Parameter Qualifier Definitions:

Qualifier	Description
J	Duplicate results and limits are expressed in terms of absolute difference.
RPD-NA	Relative Percent Difference Not Available due to result(s) being less than detection limit.

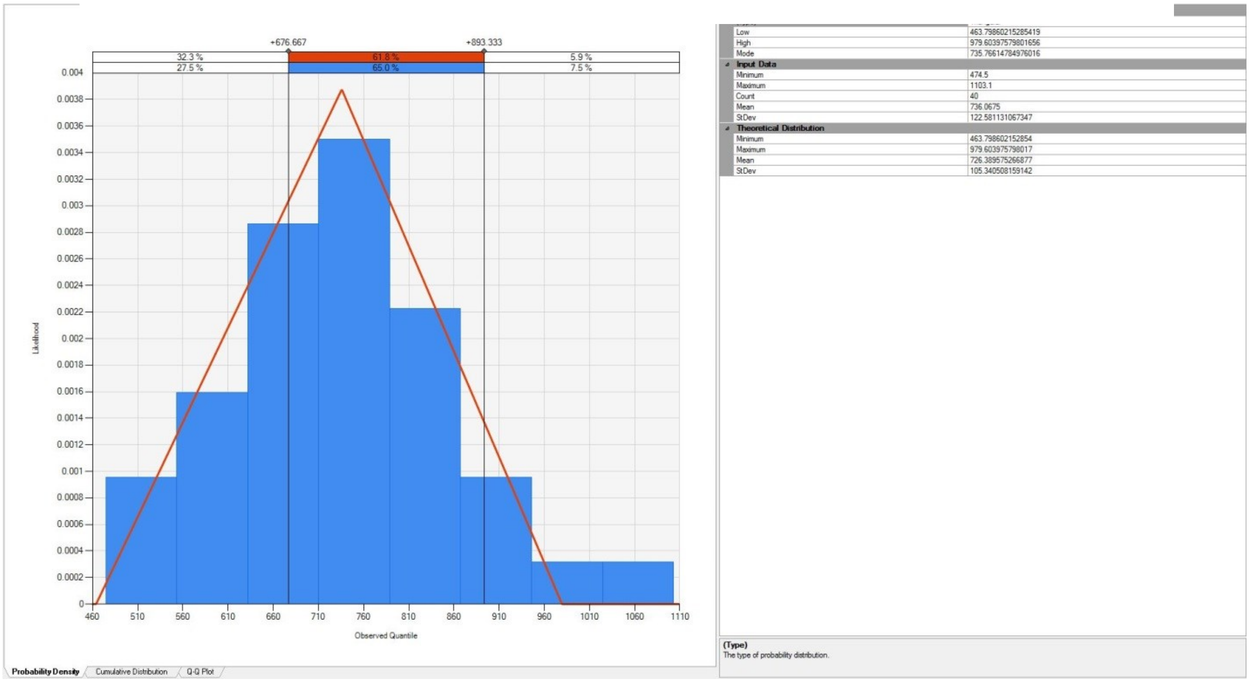
APPENDIX E: Distributions used in Life Cycle Costing Simulation



Distribution Parameters	
(Type)	Triangular
Low	576.89183031649816
High	1161.5944781904097
Mode	856.064072706409
Input Data	
Minimum	641
Maximum	1233.3
Count	40
Mean	875.6125
StDev	128.314570855184
Theoretical Distribution	
Minimum	576.891830316498
Maximum	1161.59447819041
Mean	864.850127071105
StDev	119.392345281684

(Type)
The type of probability distribution.

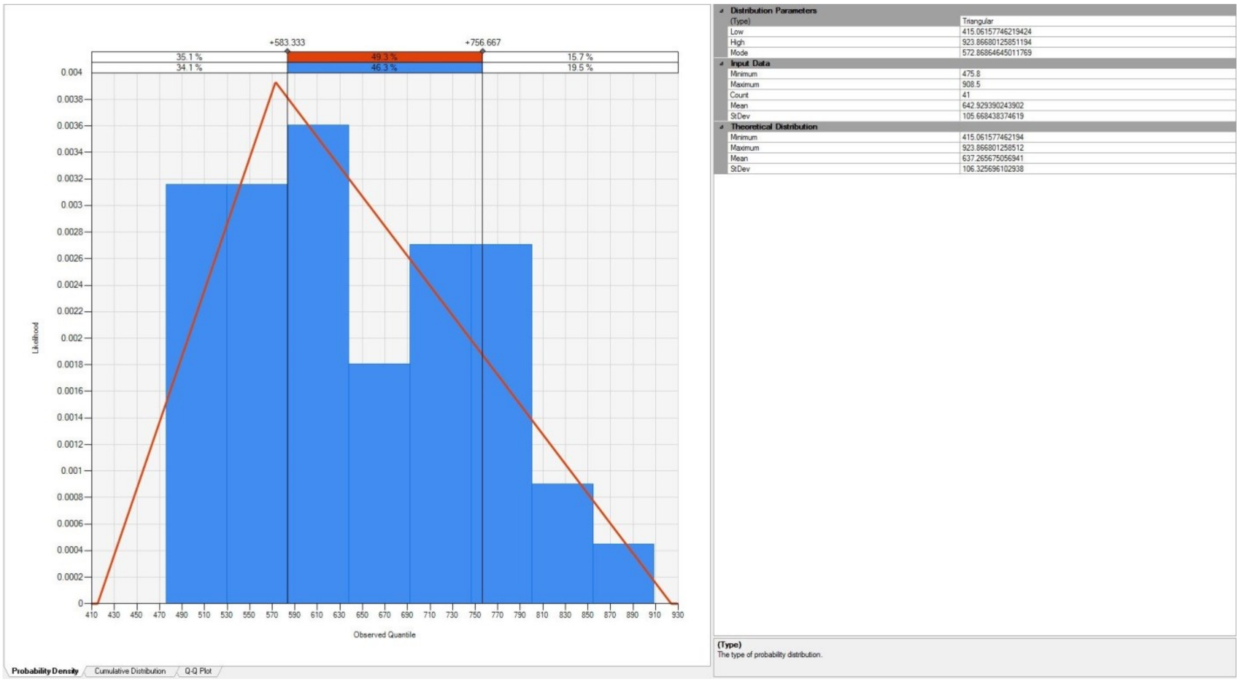
Figure E.1: January HDD Distribution



Low	463.79860215285419
High	979.60397579801656
Mode	735.76614784976016
Input Data	
Minimum	474.5
Maximum	1103.1
Count	40
Mean	736.0675
StDev	122.581131067347
Theoretical Distribution	
Minimum	463.798602152854
Maximum	979.603975798017
Mean	726.389575266877
StDev	105.340508159142

(Type)
The type of probability distribution.

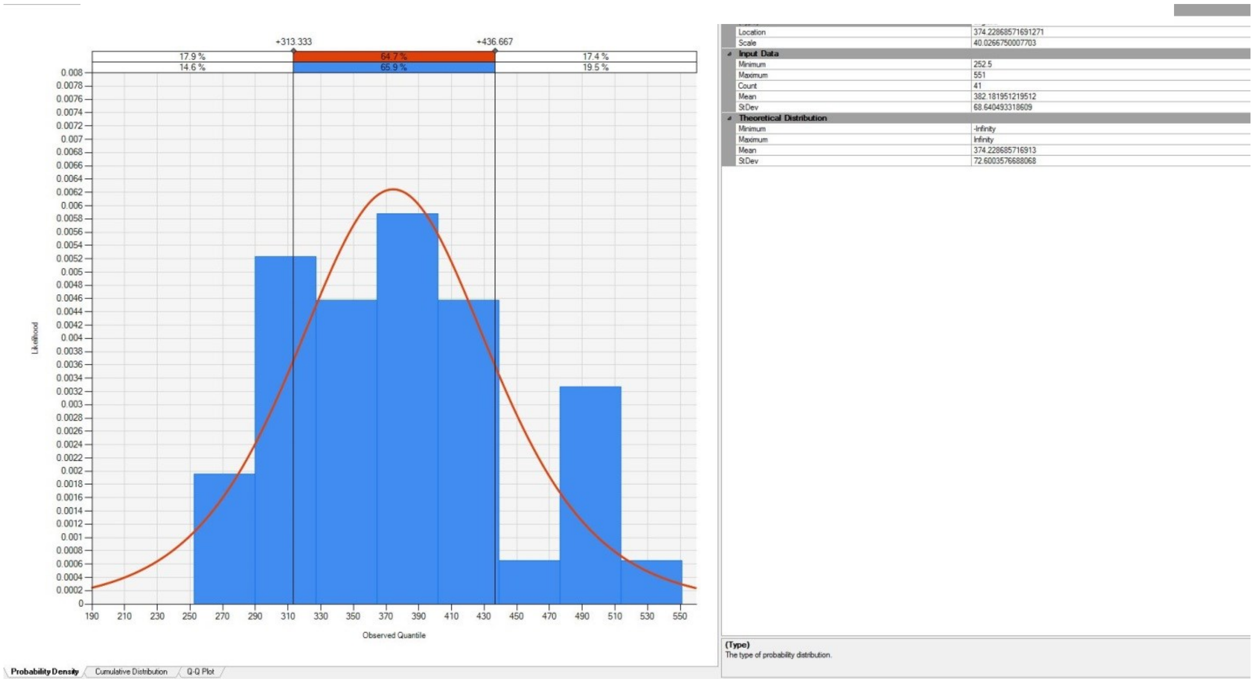
Figure E.2: February HDD Distribution



Distribution Parameters	
(Type)	Triangular
Low	415.06157746219424
High	923.86680125851194
Mode	572.86864645011769
Input Data	
Minimum	475.8
Maximum	908.5
Count	41
Mean	642.929390243902
StDev	105.668438374619
Theoretical Distribution	
Minimum	415.061577462194
Maximum	923.866801258512
Mean	637.265675056941
StDev	106.325696102938

(Type)
The type of probability distribution.

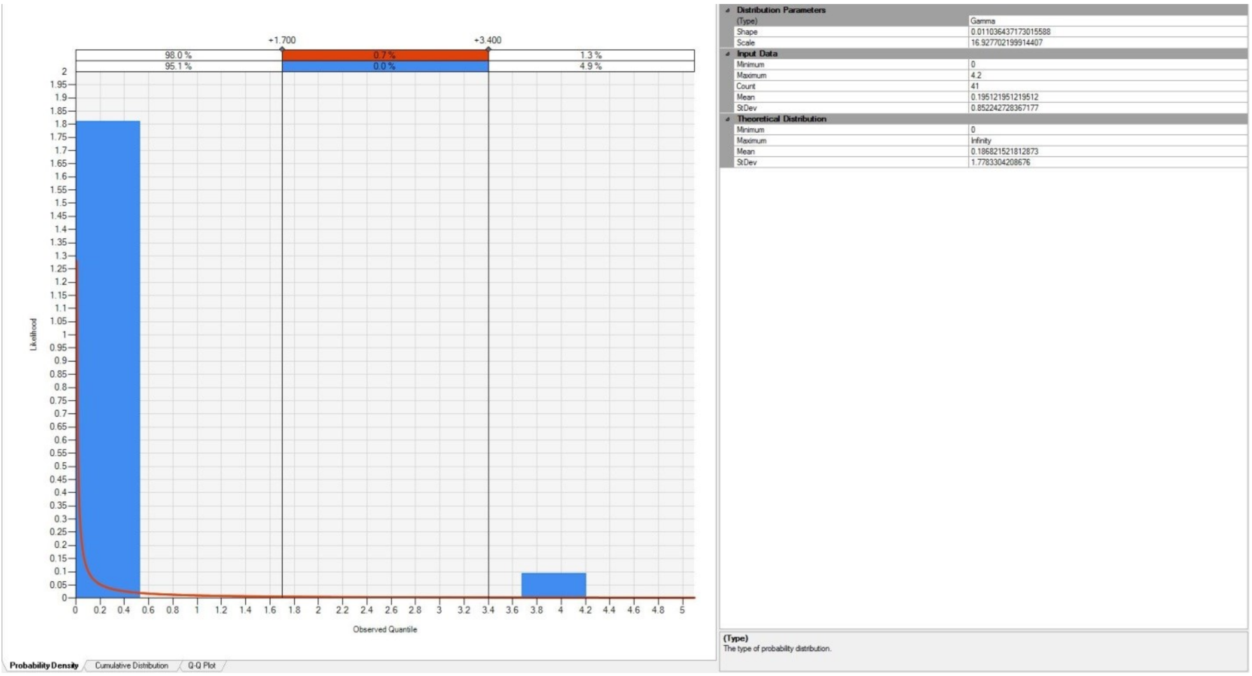
Figure E.3: March HDD Distribution



Location	374.22868571691271
Scale	40.0266750007703
Input Data	
Minimum	252.5
Maximum	551
Count	41
Mean	382.181951219512
StDev	68.640493318609
Theoretical Distribution	
Minimum	-Infinity
Maximum	Infinity
Mean	374.228685716913
StDev	72.6003576688068

(Type)
The type of probability distribution.

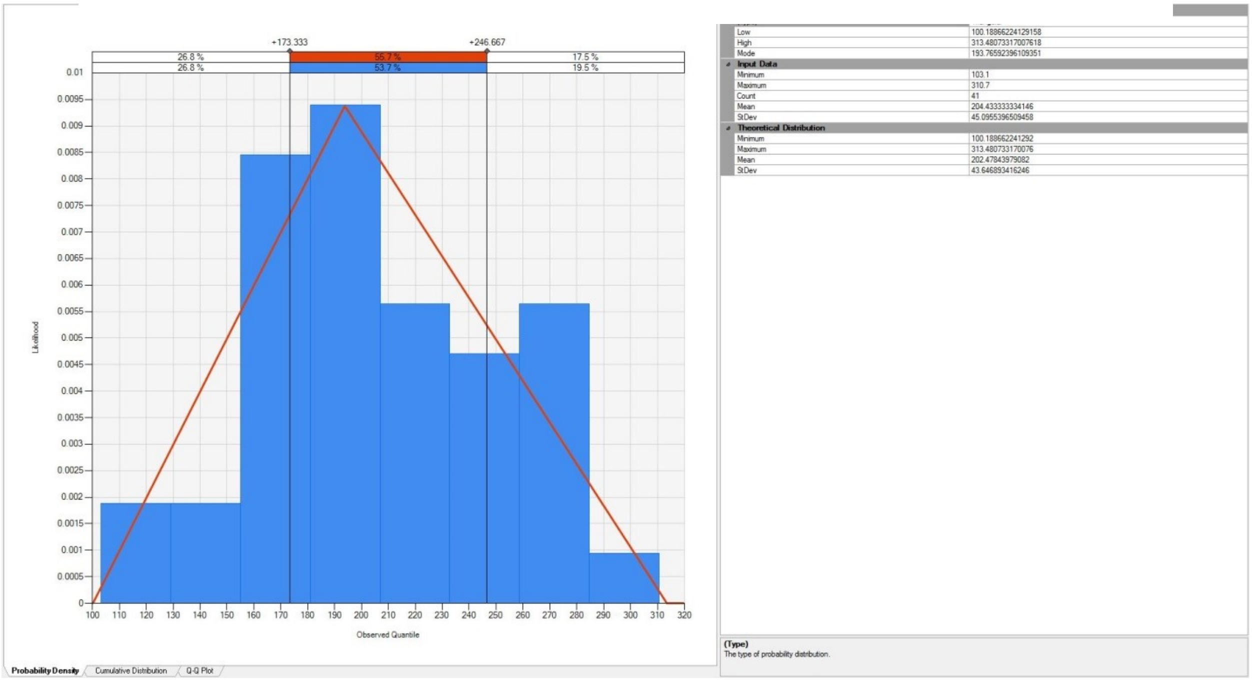
Figure E.4: April HDD Distribution



Distribution Parameters	
(Type)	Gamma
Shape	0.011036437173015588
Scale	16.927702199914407
Input Data	
Minimum	0
Maximum	4.2
Count	41
Mean	0.195121951219512
StDev	0.852242728367177
Theoretical Distribution	
Minimum	0
Maximum	Infinity
Mean	0.186821521812873
StDev	1.7783304208676

(Type)
The type of probability distribution.

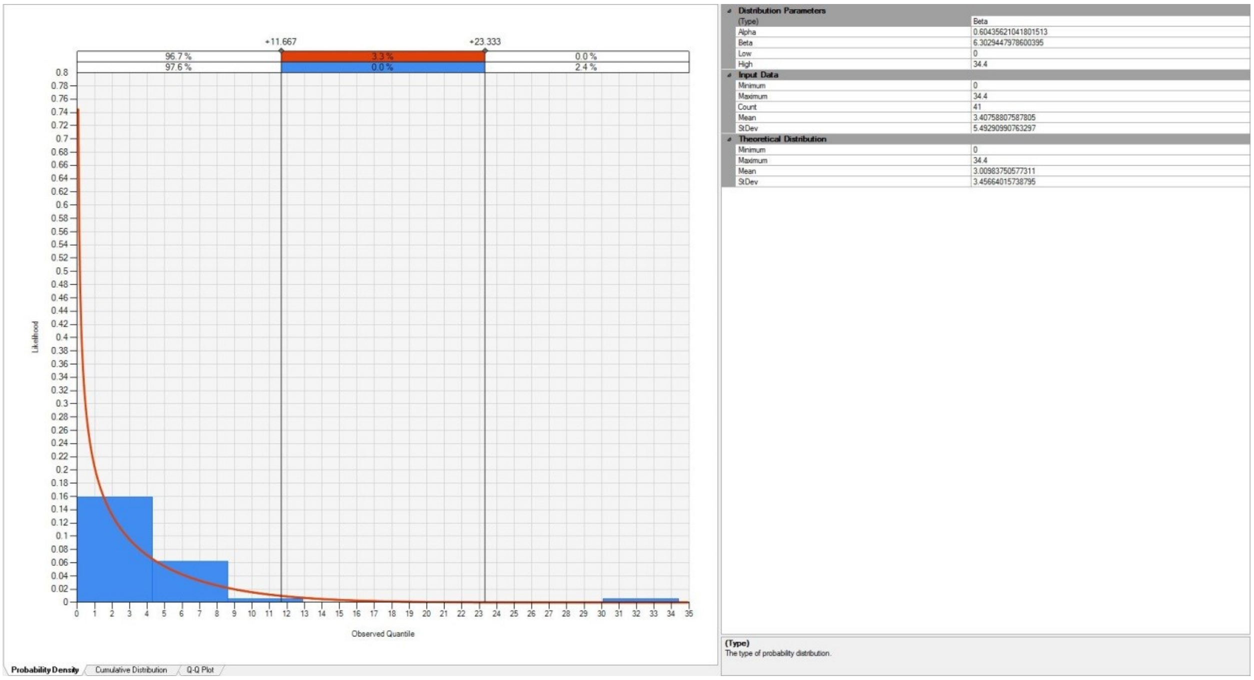
Figure E.5: April CDD Distribution



Low	100.18866224129158
High	313.48073317007618
Mode	193.76592396109351
Input Data	
Minimum	103.1
Maximum	310.7
Count	41
Mean	204.433333334146
StDev	45.0955396509458
Theoretical Distribution	
Minimum	100.188662241292
Maximum	313.480733170076
Mean	202.47843979082
StDev	43.646893416246

(Type)
The type of probability distribution.

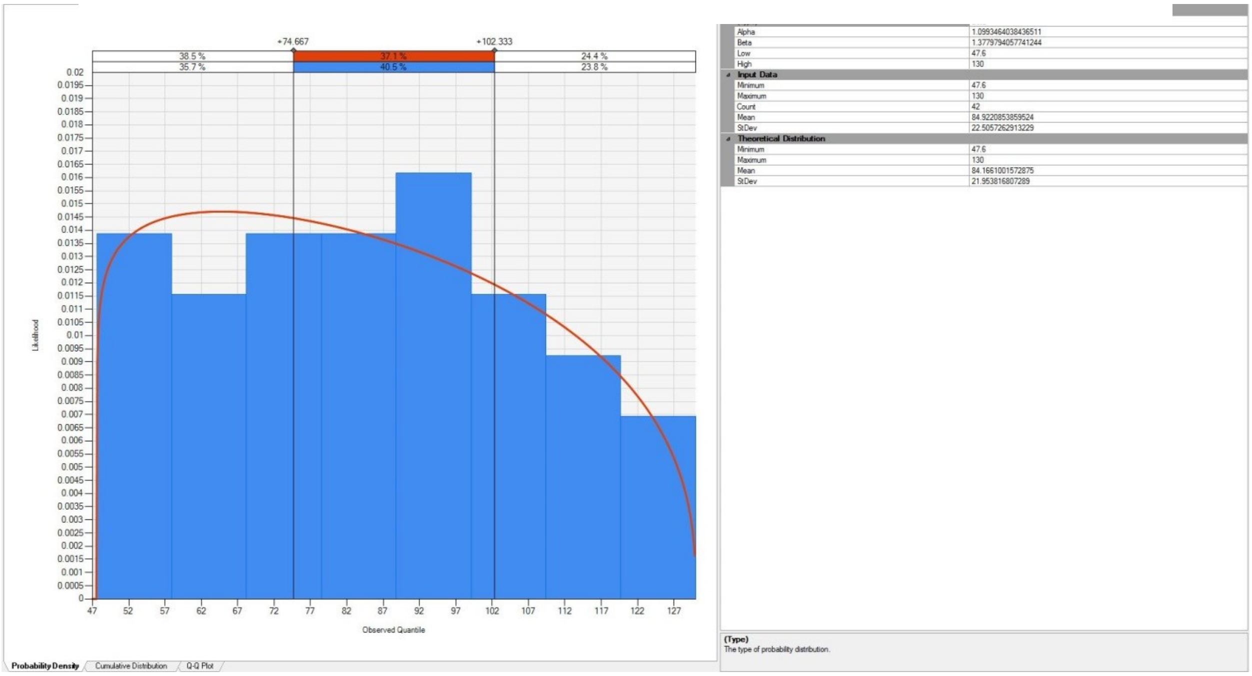
Figure E.6: May HDD Distribution



Distribution Parameters	
(Type)	Beta
Alpha	0.60435621041801513
Beta	6.3029447978600395
Low	0
High	34.4
Input Data	
Minimum	0
Maximum	34.4
Count	41
Mean	3.40758807587805
StDev	5.49290990763297
Theoretical Distribution	
Minimum	0
Maximum	34.4
Mean	3.00983750577311
StDev	3.45664015738795

(Type)
The type of probability distribution.

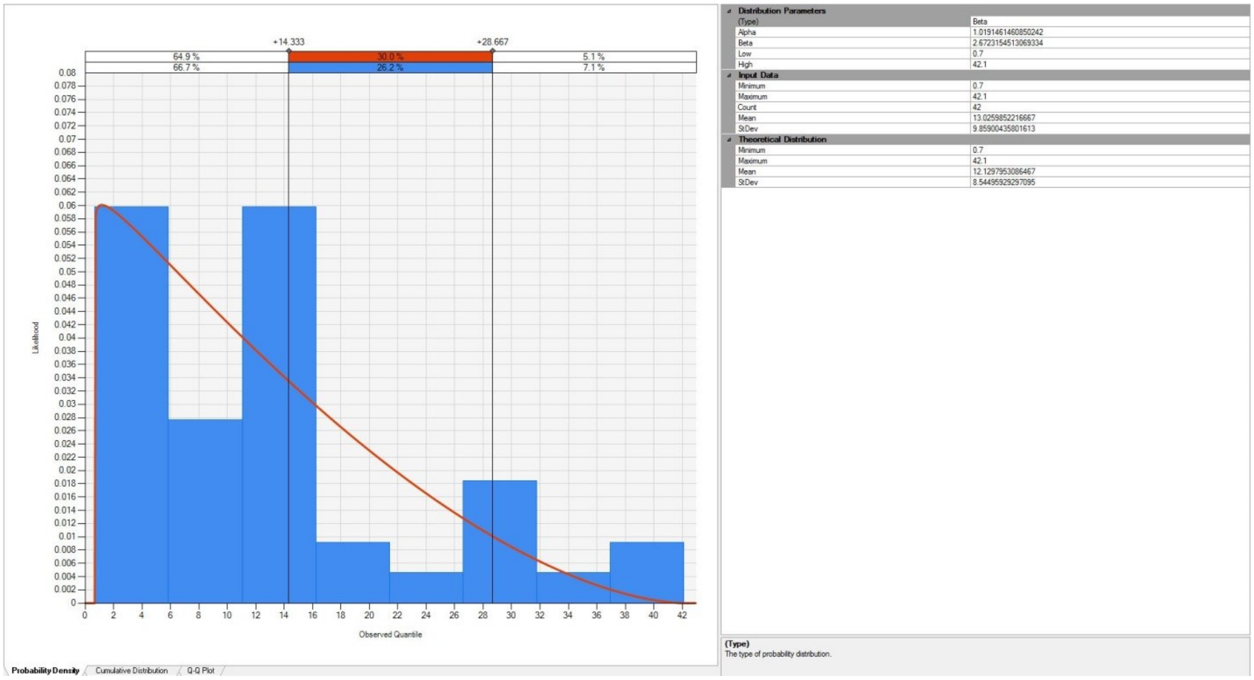
Figure E.7: May CDD Distribution



Alpha	1.0993464038436511
Beta	1.3779794057741244
Low	47.6
High	130
Input Data	
Minimum	47.6
Maximum	130
Count	42
Mean	84.9220853859524
StDev	22.5057262913229
Theoretical Distribution	
Minimum	47.6
Maximum	130
Mean	84.1661001572875
StDev	21.953816807289

(Type)
The type of probability distribution.

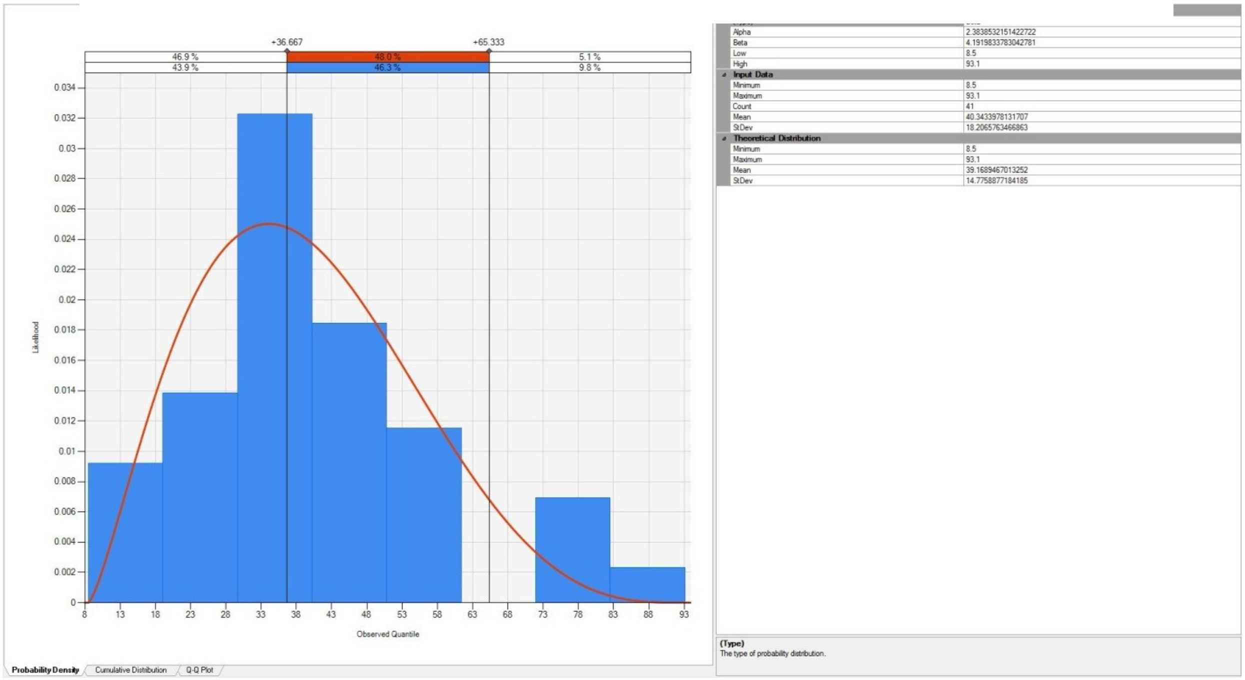
Figure E.8: June HDD Distribution



Distribution Parameters	
(Type)	Beta
Alpha	1.0191461460850242
Beta	2.6723154513069334
Low	0.7
High	42.1
Input Data	
Minimum	0.7
Maximum	42.1
Count	42
Mean	13.0259852216667
StDev	9.85900435801613
Theoretical Distribution	
Minimum	0.7
Maximum	42.1
Mean	12.1297953086467
StDev	8.54495929297095

(Type)
The type of probability distribution.

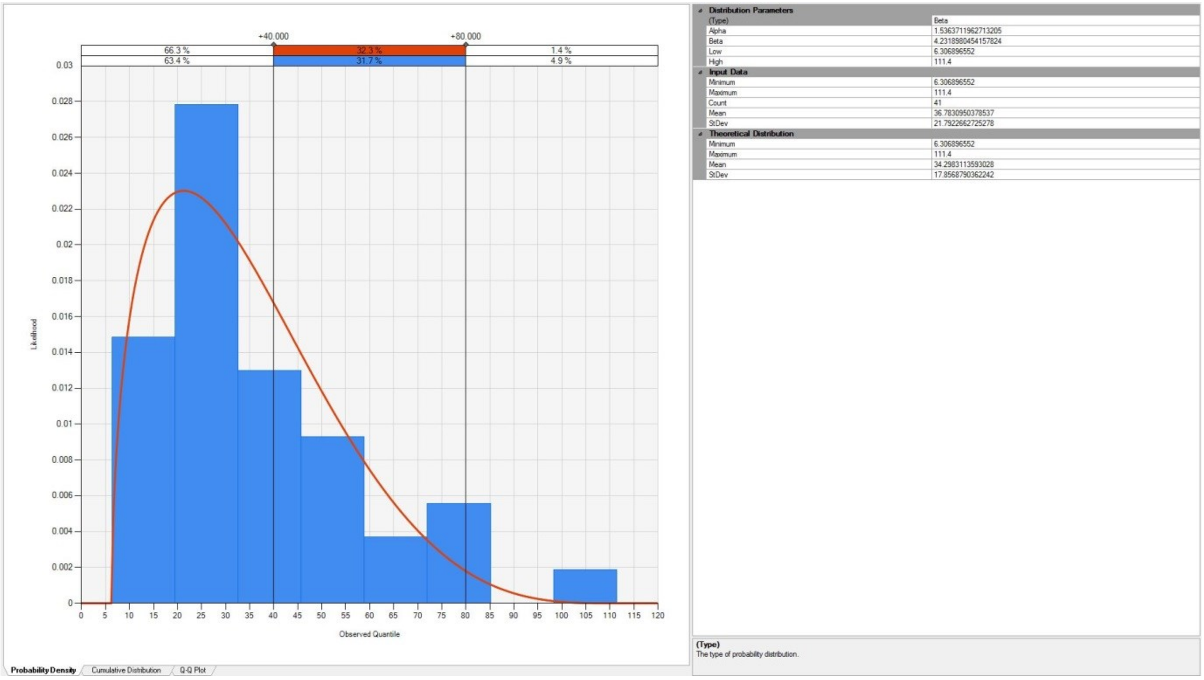
Figure E.9: June CDD Distribution



Alpha	2.3838532151422722
Beta	4.1919833783042781
Low	8.5
High	93.1
Input Data	
Minimum	8.5
Maximum	93.1
Count	41
Mean	40.3433978131707
StDev	18.2065763466863
Theoretical Distribution	
Minimum	8.5
Maximum	93.1
Mean	39.1689467013252
StDev	14.7758877184185

(Type)
The type of probability distribution.

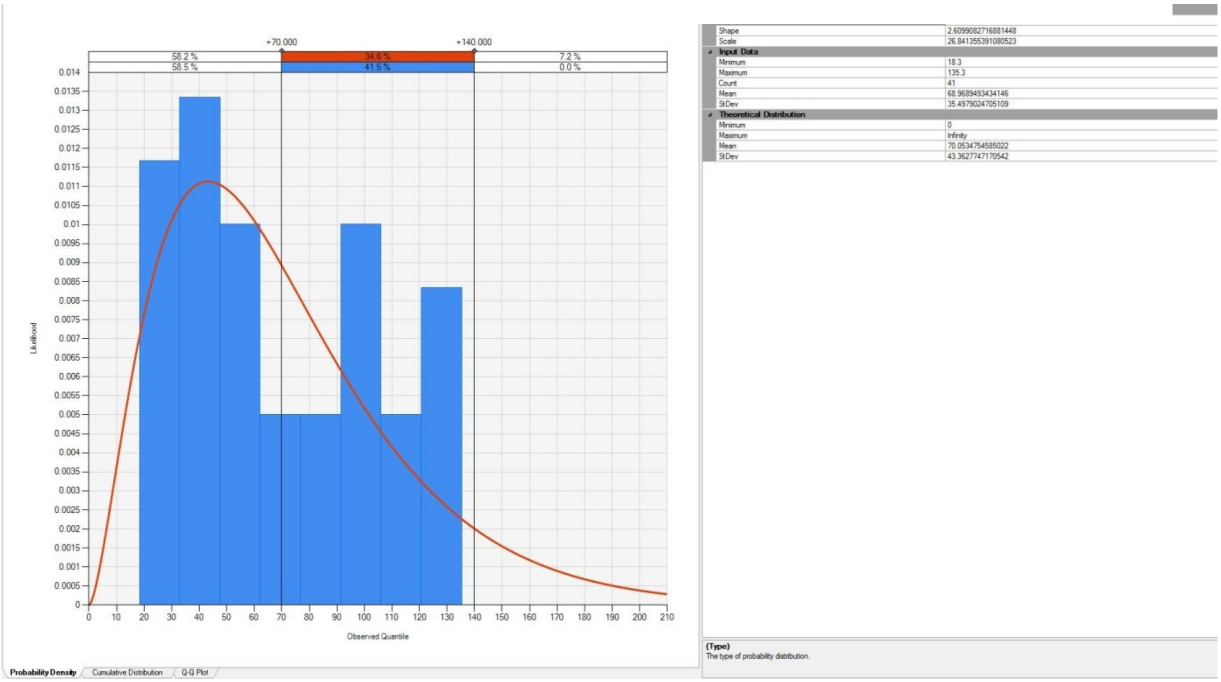
Figure E.10: July HDD Distribution



Distribution Parameters	
(Type)	Beta
Alpha	1.5363711962713205
Beta	4.2318980454157824
Low	6.306896552
High	111.4
Input Data	
Minimum	6.306896552
Maximum	111.4
Count	41
Mean	36.7830950378537
StDev	21.7922662725278
Theoretical Distribution	
Minimum	6.306896552
Maximum	111.4
Mean	34.2983113593028
StDev	17.8568790362242

(Type)
The type of probability distribution.

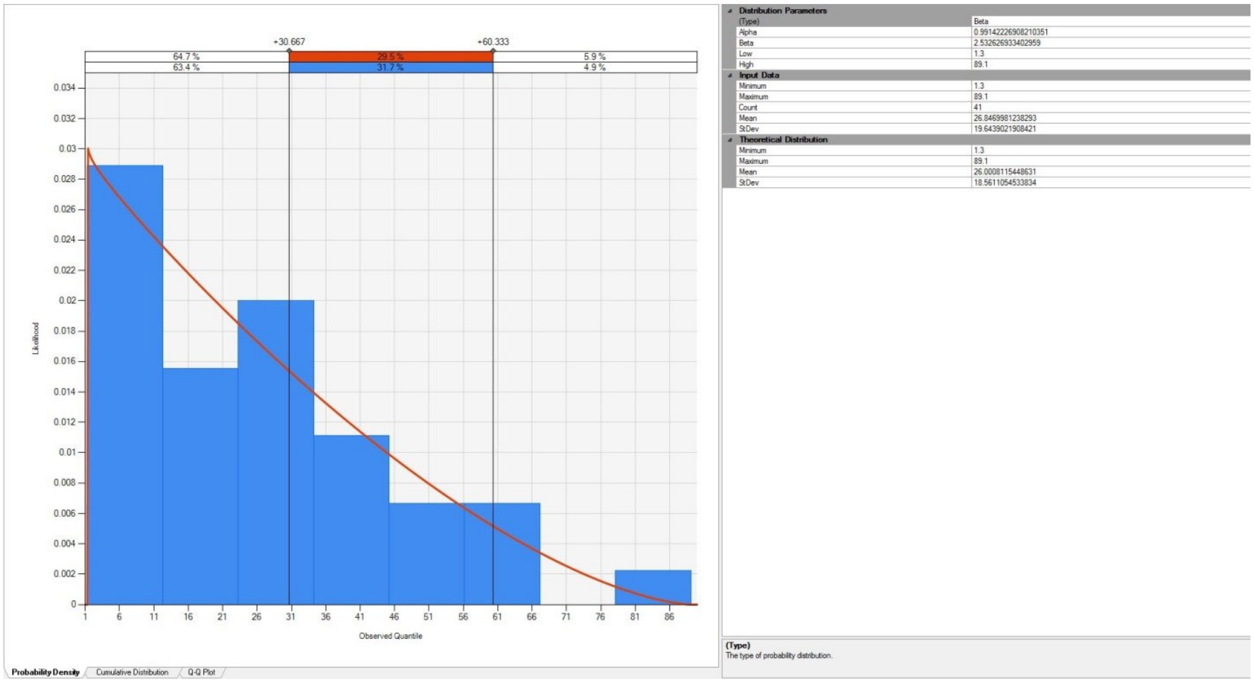
Figure E.11: July CDD Distribution



Shape	2.6099082716881448
Scale	26.841355391080523
Input Data	
Minimum	18.3
Maximum	135.3
Count	41
Mean	68.9689493434146
StDev	35.4979024705109
Theoretical Distribution	
Minimum	0
Maximum	Infinity
Mean	70.0534754585022
StDev	43.3627747170542

(Type)
The type of probability distribution.

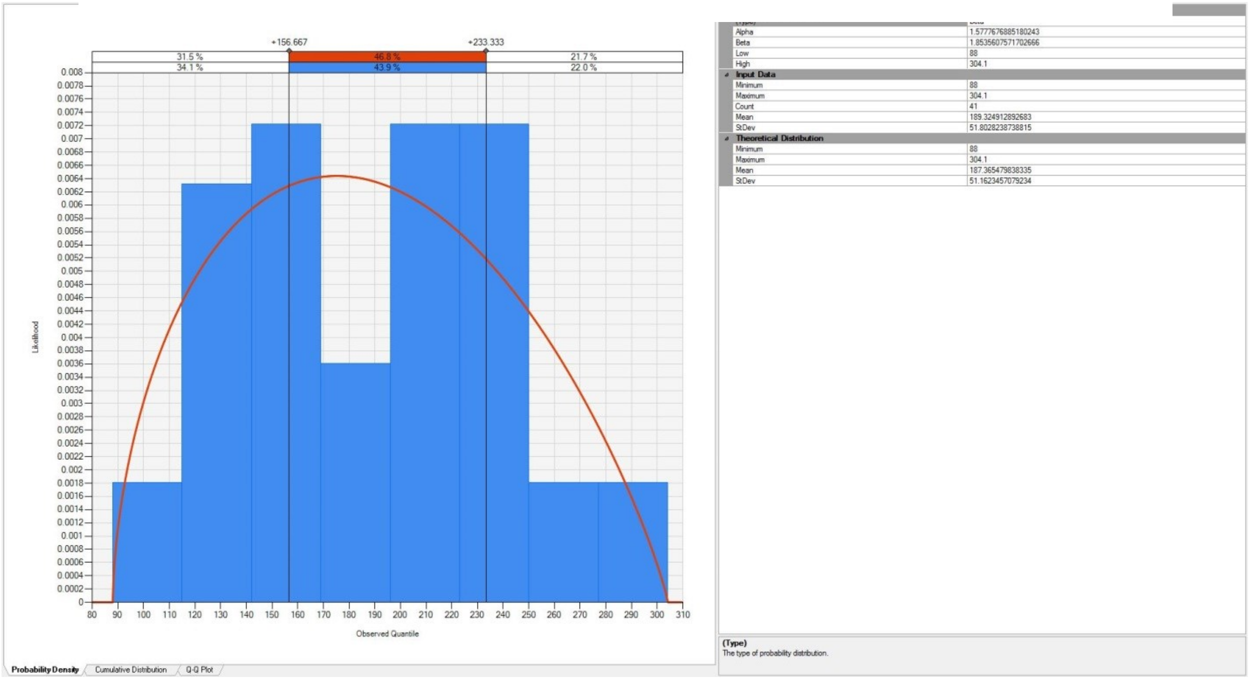
Figure E.12: August HDD Distribution



Distribution Parameters	
(Type)	Beta
Alpha	0.99142226908210351
Beta	2.532626933402959
Low	1.3
High	89.1
Input Data	
Minimum	1.3
Maximum	89.1
Count	41
Mean	26.8469981238293
StDev	19.6439021908421
Theoretical Distribution	
Minimum	1.3
Maximum	89.1
Mean	26.0008115448631
StDev	18.5611054533834

(Type)
The type of probability distribution.

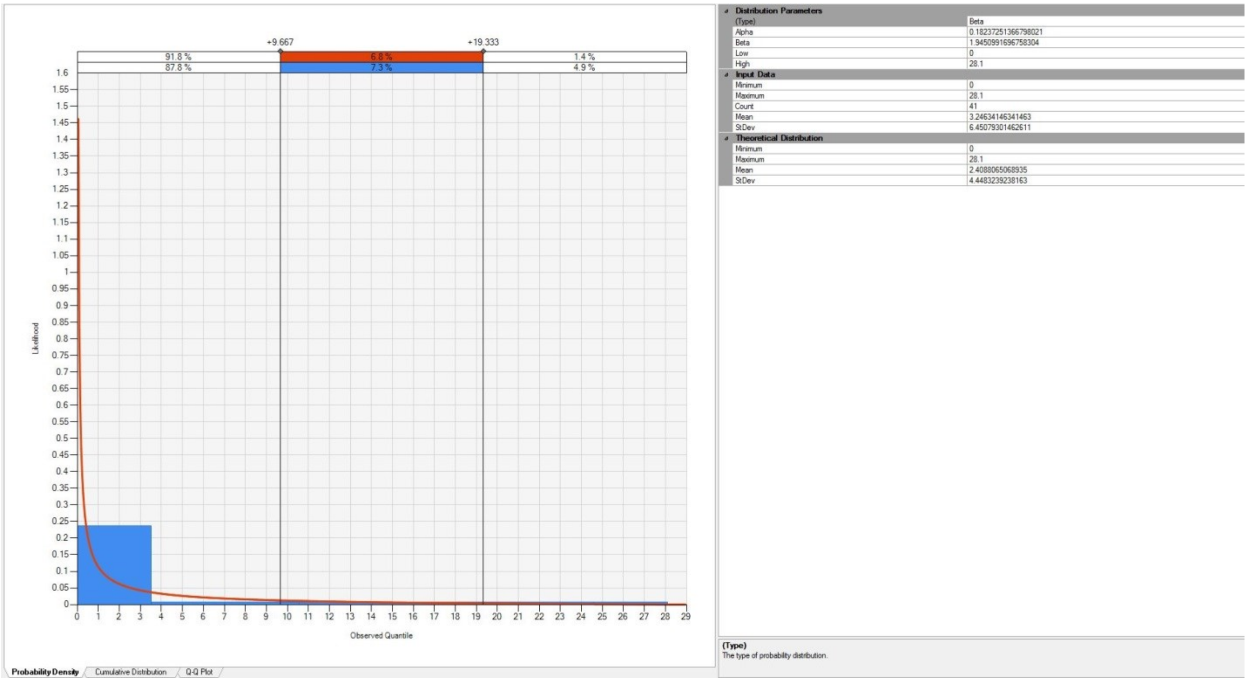
Figure E.13: August CDD Distribution



Alpha	1.5777676885180243
Beta	1.8535607571702666
Low	88
High	304.1
Input Data	
Minimum	88
Maximum	304.1
Count	41
Mean	189.324912892683
StDev	51.8028238738815
Theoretical Distribution	
Minimum	88
Maximum	304.1
Mean	187.365479838335
StDev	51.1623457079234

(Type)
The type of probability distribution.

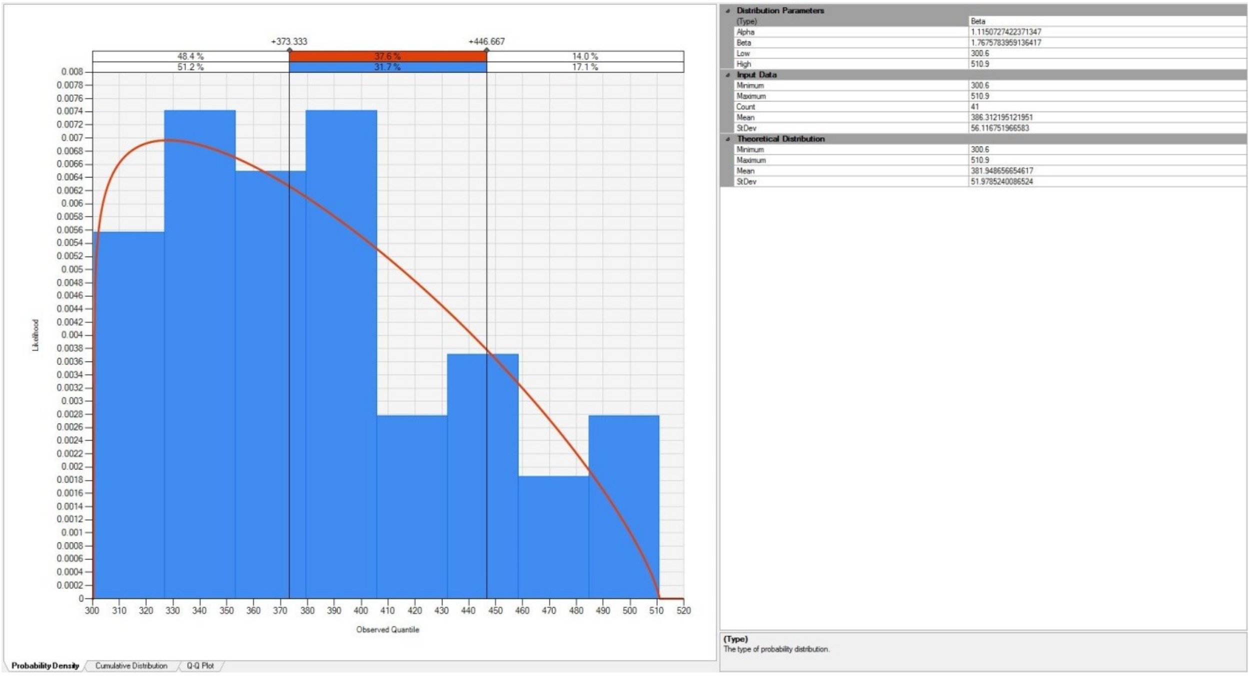
Figure E.14: September HDD Distribution



Distribution Parameters	
(Type)	Beta
Alpha	0.18237251366798021
Beta	1.9450991696758304
Low	0
High	28.1
Input Data	
Minimum	0
Maximum	28.1
Count	41
Mean	3.24634146341463
StDev	6.45079301462611
Theoretical Distribution	
Minimum	0
Maximum	28.1
Mean	2.4088065068935
StDev	4.4483239238163

(Type)
The type of probability distribution.

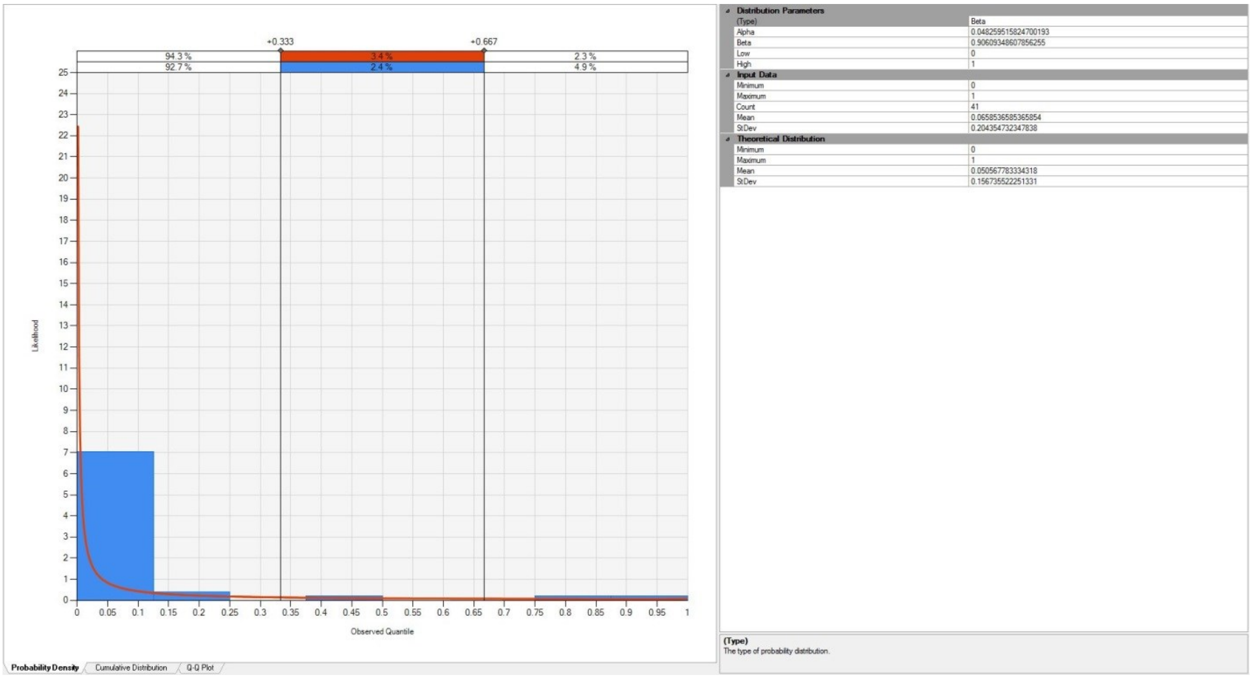
Figure E.15: September CDD Distribution



Distribution Parameters	
(Type)	Beta
Alpha	1.1150727422371347
Beta	1.7675783959136417
Low	300.6
High	510.9
Input Data	
Minimum	300.6
Maximum	510.9
Count	41
Mean	386.312195121951
StDev	56.116751966583
Theoretical Distribution	
Minimum	300.6
Maximum	510.9
Mean	381.948656654617
StDev	51.9785240086524

(Type)
The type of probability distribution.

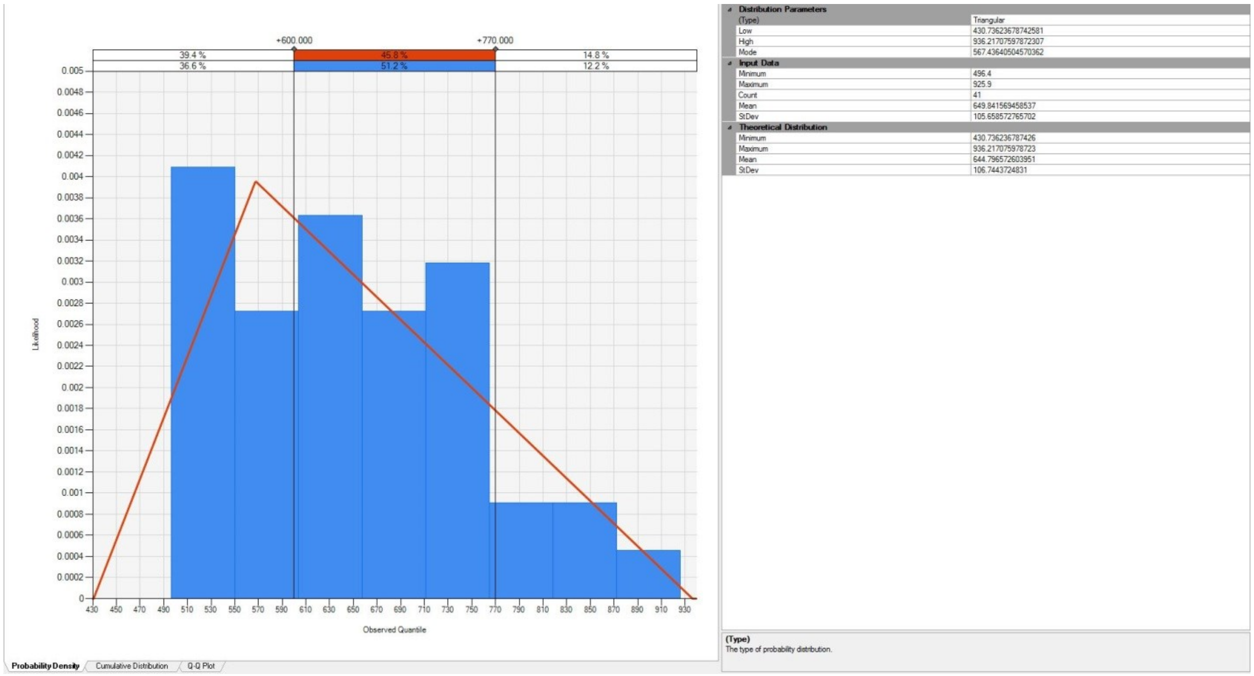
Figure E.16: October HDD Distribution



Distribution Parameters	
(Type)	Beta
Alpha	0.048259515824700193
Beta	0.90609348607856255
Low	0
High	1
Input Data	
Minimum	0
Maximum	1
Count	41
Mean	0.0658536585365854
StDev	0.204354732347838
Theoretical Distribution	
Minimum	0
Maximum	1
Mean	0.050567783334318
StDev	0.156735522251331

(Type)
The type of probability distribution.

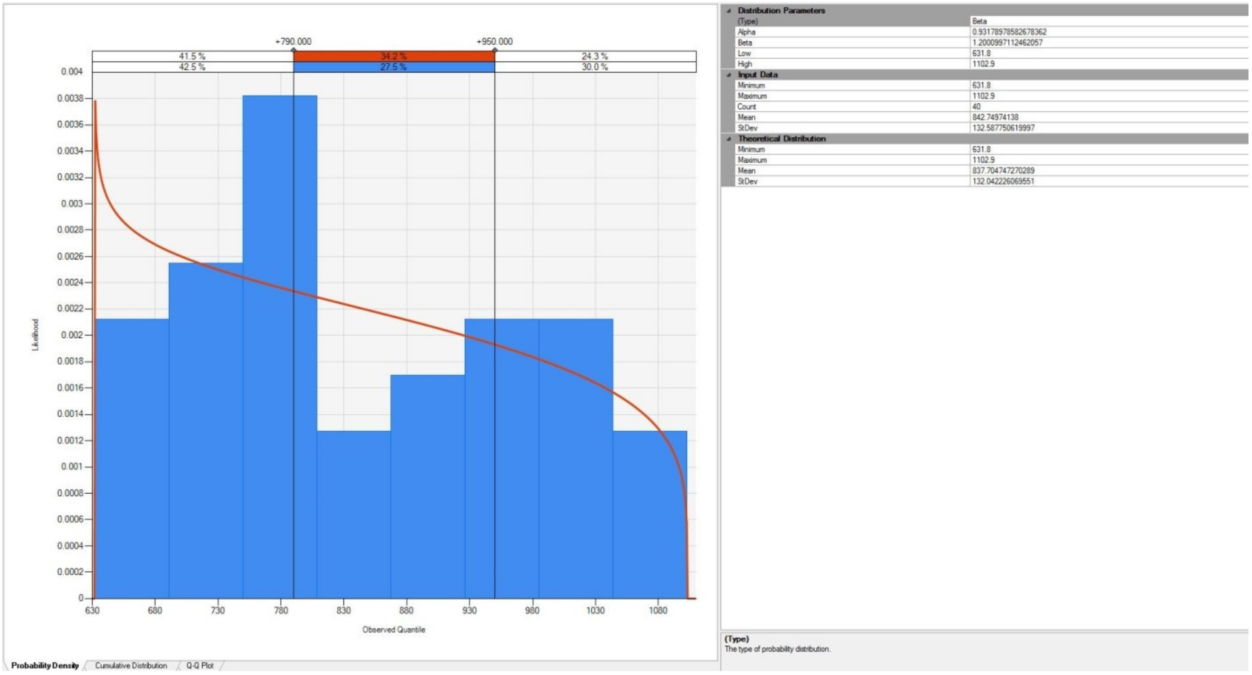
Figure E.17: October CDD Distribution



Distribution Parameters	
(Type)	Triangular
Low	430.73623678742581
High	936.21707597872307
Mode	567.43640504570362
Input Data	
Minimum	496.4
Maximum	925.9
Count	41
Mean	649.841569458537
StDev	105.658572765702
Theoretical Distribution	
Minimum	430.736236787426
Maximum	936.217075978723
Mean	644.796572603951
StDev	106.7443724831

(Type)
The type of probability distribution.

Figure E.18: November HDD Distribution



Distribution Parameters	
(Type)	Beta
Alpha	0.93178978582678362
Beta	1.2000997112462057
Low	631.8
High	1102.9
Input Data	
Minimum	631.8
Maximum	1102.9
Count	40
Mean	842.74974138
StDev	132.587750619997
Theoretical Distribution	
Minimum	631.8
Maximum	1102.9
Mean	837.704747270289
StDev	132.042226069551

(Type)
The type of probability distribution.

Figure E.19: December HDD Distribution

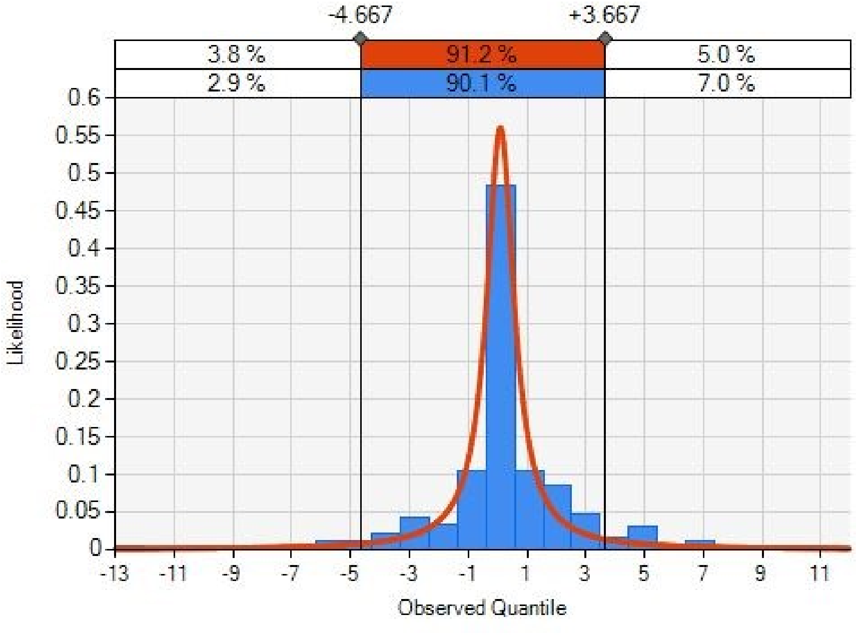


Figure E.20: Monthly change in the price of electricity distribution

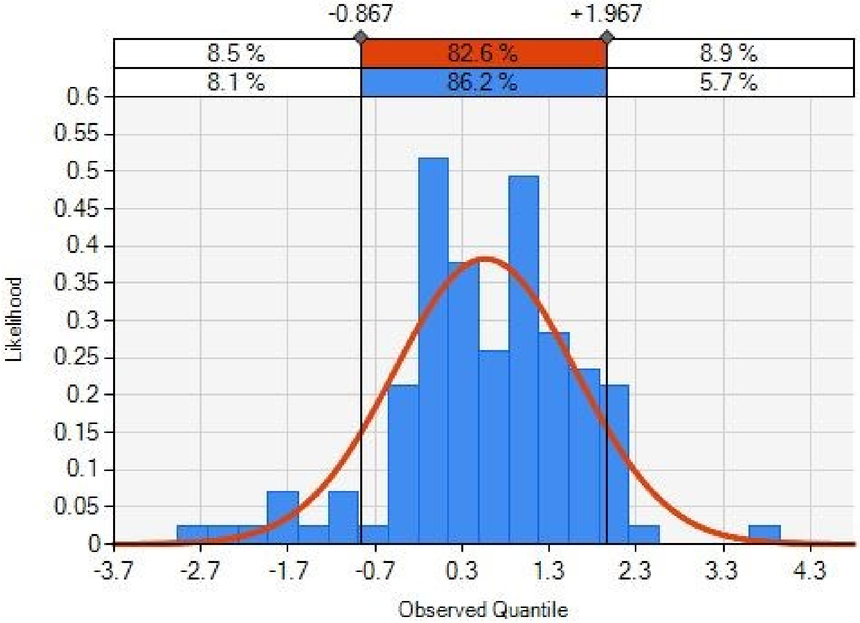


Figure E.21: Monthly change in the price of labor distribution

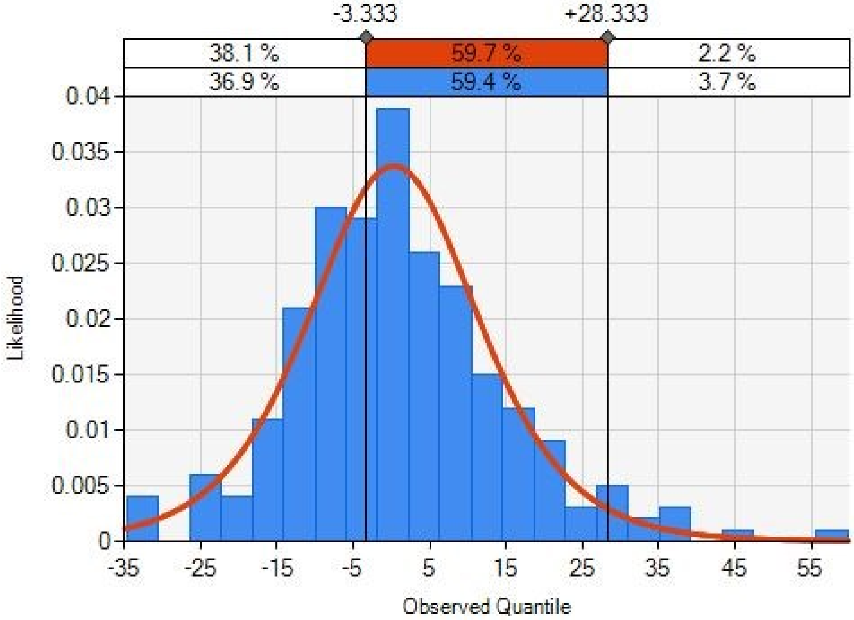


Figure E.22: Monthly change in the price of natural gas distribution