
McGill Energy Project

# RVC ASHRAE Level II Energy Audit

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McGill

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## Executive summary

Since 2002, McGill has invested approximately $10 million in sustainability initiatives and energy consumption reduction measures. These actions were triggered by the Ministère de l'Education, du Loisir et des Sports. In 2006, this governmental institution mandated that post-secondary institutions should reduce the extent of their energy consumption by 14% relative to 2002-2003 levels. A 5 year energy management plan has been implemented by McGill highlighting the necessity of major modifications including a building energy audit program. The McGill Energy Project (MEP) is a student-led cooperation of students, faculty and staff which seeks to develop sustainable solutions by creating applied projects. As a group of senior Bioresource engineering students, we applied for and were granted by the MEP, the energy audit of the McGill's Royal Victoria College residence; a two part project mandated by the assistant director of residences, David Balcombe.

Phase one of this project was dedicated to the understanding and analysis of the buildings operations seeking to find major energy losses. The undergone procedure follows the ASHRAE level 1 standards, thus including an analysis of energy usage and associated costs based on historical data, buildings' infrastructure and their characteristics. Upon investigation, a variety of problems within RVC, the cafeteria and piping connections with the Strathcona building were identified. The most crucial problems were selected as requiring improvements. One of the most pressing matters was found to be a major heat loss detected in a domestic hot water pipe circulating through both RVC and the Strathcona building. A capital intensive usage of the steam during summer months had been observed and was subject to investigation for alternative energy sources. The lighting system in placed has been evaluated as outdated and inefficient. On January 31st, 2014, a meeting was held between David Balcombe, members of MEP and Frederic Samson representative of McGill's Utilities and Energy Management. This reunion aimed at presenting the results of the energy analysis of RVC as well as early improvement suggestions in order to define the scope of the second phase of the project. A consensus was reached on the most urgent and realistic modifications to be performed, namely, the retrofitting of the hot water domestic network and lighting system.

The following report contains the final deliverables of the second phase of the energy audit which aims at increasing the efficiency of the Royal Victoria Residence (RVC) and its cafeteria from an energy and financial standpoint. Two options will be proposed with regards to the inefficient usage of steam for domestic water heating. Both alternatives suggest domestic hot water independency for the east wing of Strathcona by incorporating electric water heater to the present infrastructure. Alternative 1 adds two independent closed loops to the system in order to circulate hot water for the usage of the cafeteria and the rest of Strathcona. In this solution there will be no hot water flow between RVC and Strathcona and for this, electricity was found to be the optimal energy source. Alternative 2 insures the supply of hot water to Strathcona using the existing steam heat exchanger located in RVC. Both options are optimized to minimize the cost of investment and will be reusing pipes from the current network. In regards to lighting, several solutions will be considered, including replacing T12 fixtures and incandescent bulbs with T5 and LED fixtures. Each retrofitting scenario will undergo an economic analysis in order to assess the viability of the projects.

## Acknowledgments

We would like to express our gratitude to Robert Patterson for his help, availability and guidance throughout the project. Mr. Patterson dedicated a lot of his time toward providing us with key informations and getting us accustomed with building and its utilities.

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## Terminology

This report will make use of some location and project specific term. The following map (Figure a) displays the location and agreed upon terminology of the utilities and part of the buildings.

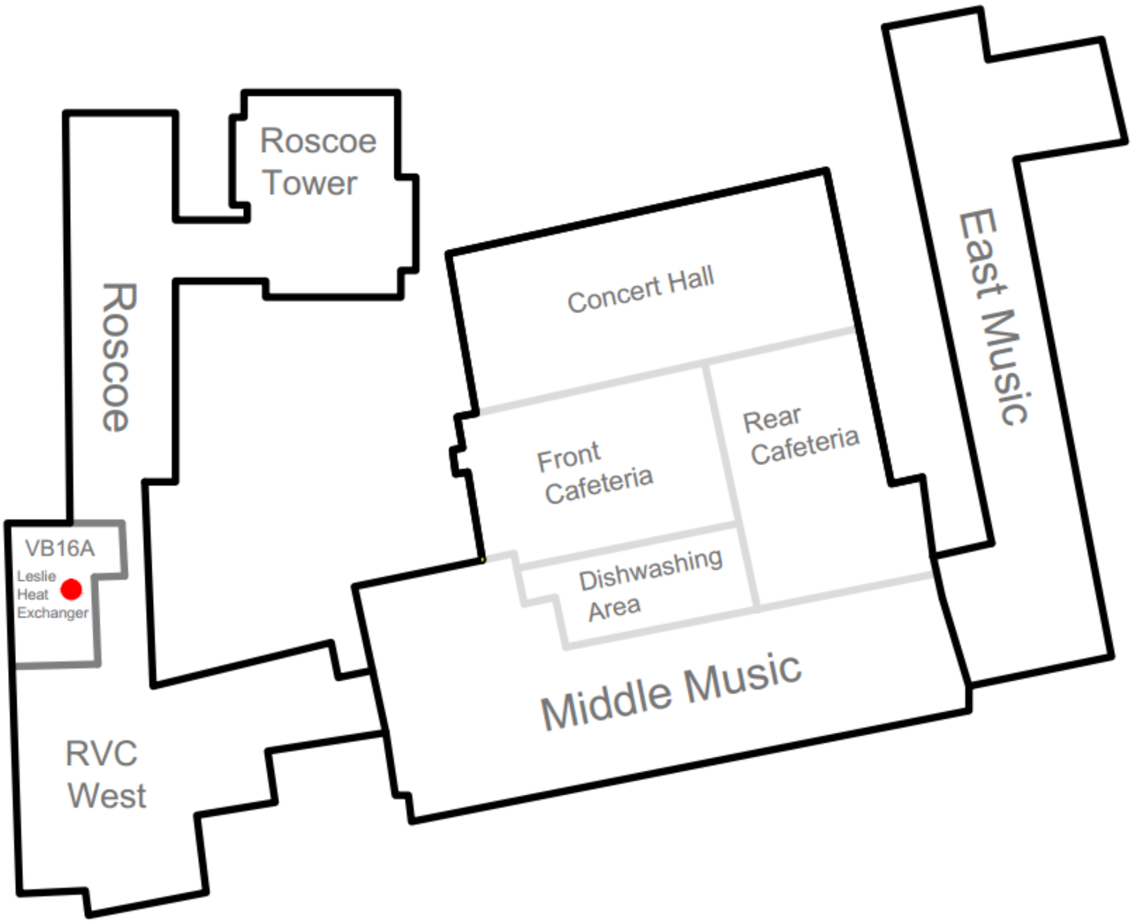



*Figure a: Building naming terminology*

<u>Note:</u> It is important to mention that many buildings on campus (including residence halls) are separate entities and are individually charged for their energy consumption. McGill's Utilities and Energy Management holds the primary responsibility for coordinating energy billing, quantifying the monthly consumption and developing a billing structure for each of its clients. As a result, the Royal Victoria Residence and its cafeteria should be charged separately from Strathcona.

# 1. Overview of Design 2: ASHRAE Level 1

## 1.1 Context, energy analysis and deliverables

RVC currently uses steam and electricity as its two main energy sources. Hot water for domestic and heating purposes is provided by steam circulating from the McGill Powerhouse to RVC, where it is used in four separate mechanical rooms. The flow directly comes from McGill's transportation pipe to RB16, RVC's main mechanical room, where it then splits to feed the Roscoe wing, the Strathcona building and the New Music building. Each of these mechanical rooms produces hot domestic water, heat, and air supply for their respective buildings. However, the history of the infrastructure adds a degree of complexity to the steam and hot water network. (Figure 1.1.1) illustrates the steam, hot water, and condensate return networks for each respective building.

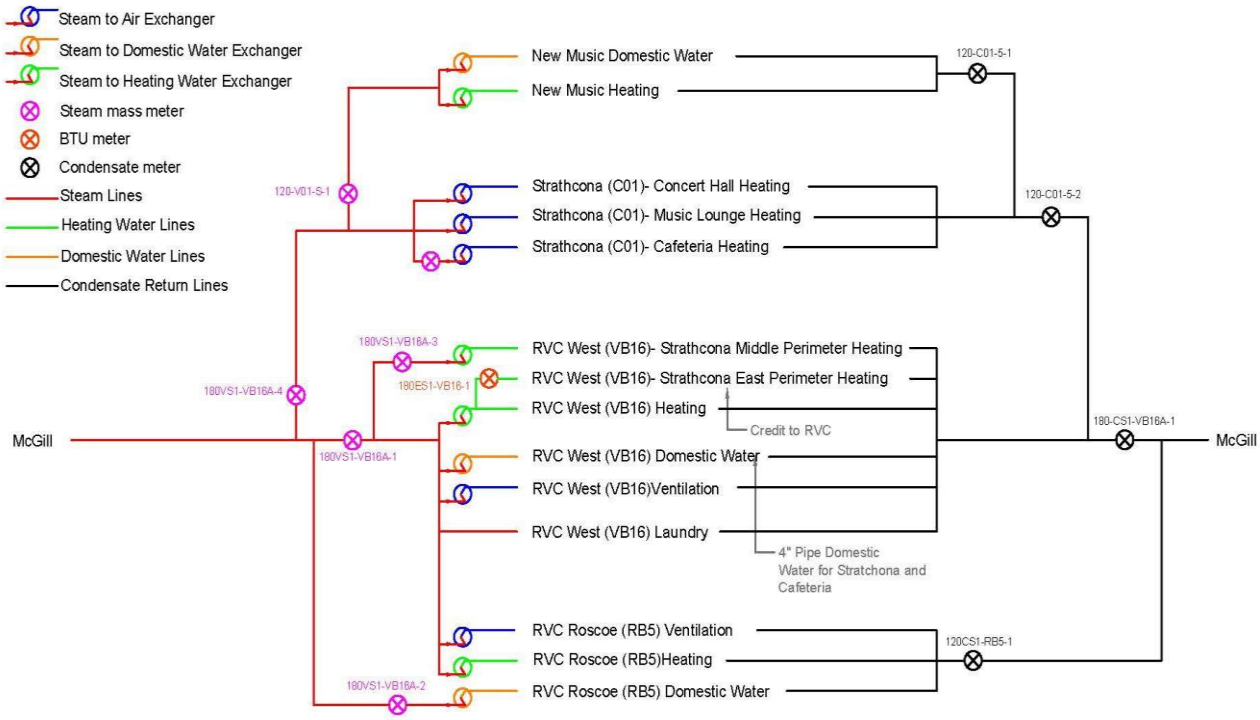
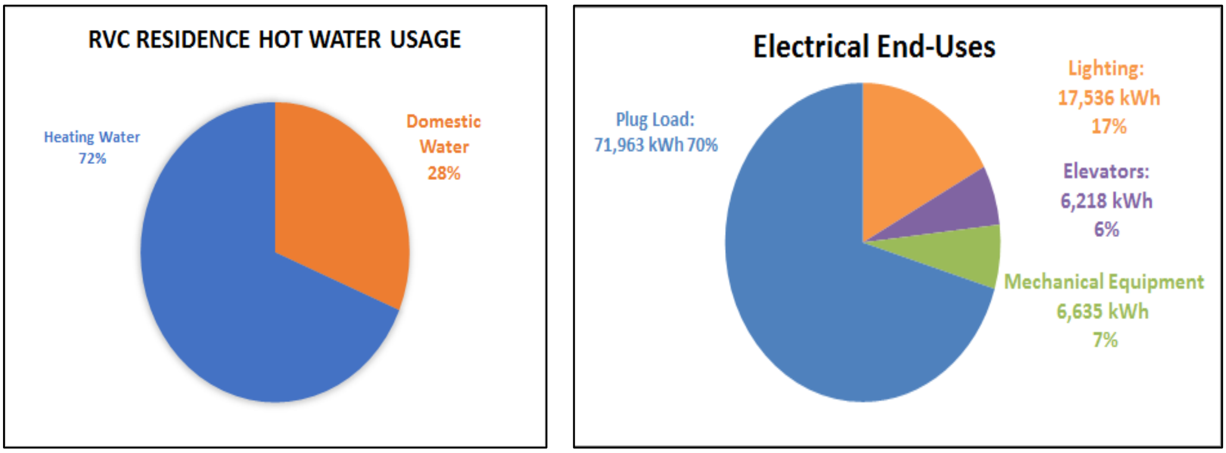



*Figure 1.1.1: Metering and paths of the hot water and condensate network.*

Steam accounts for more than 60% of the total energy used in RVC (Appendix A.1) which is equivalent to 83.4% of the annual energy bill. An analysis by end usage allowed the individual determination of the steam consumption of the Roscoe wing and RVC west. Using bills from previous years as well as metering data obtained from McGill's Pulse software, RVC West usage was estimated to account for 74% of the total steam delivered to RVC (Appendix A.2). Moreover, it was observed that the steam consumption in summer was significantly lower in comparison to the rest of the year. The amount of steam used from the month of May to September was considered not economically viable. During this period steam-to-water heat exchangers are only used to produce domestic hot water as opposed to water for heating purposes in winter. It was estimated that steam used to generate hot domestic water accounts for only 28% of the total steam consumption (Figure 1.1.2.a). The yearly fluctuations of steam rates and the low summer requirements suggested that other alternatives would be more suited to sustaining the building. In addition to this issue, the hot water network was identified as being highly energy inefficient. An extensive network of pipes originating from RVC currently feeds the cafeteria as well as the Strathcona music building complex. This complex includes the Middle and East Music buildings. Major circulation and heat loss issues were identified in this system which were mostly due to inappropriate pipe diameters and the extent of the system which spans approximately 613 meters in total. Furthermore, a lack of understanding with respect to heat loss and demand along this network prohibits delivering separate bills to Strathcona, RVC and its cafeteria.

Regarding electricity, similar end-use analysis have been completed (Figure 1.1.2.b). As is typical for residential buildings, the majority of electricity usage is a product of plug load, followed by lighting. Plug load is a factor that is hard to control, especially in the case of student residences where the loads depend on personal appliances. However, a survey of lighting fixtures revealed that RVC uses predominantly T8, T12 and incandescent lighting. Many of these fixtures are outdated and could benefit from an upgrade toward more efficient installations.




*a* *b*

*Figure 1.1.2: Percentage breakdown of the RVC hot water (a) and electrical (b) usage*

### 1.2 Suggestions

Upon the completion of the ASHRAE level 1 energy audit, a list of site-specific and general practice recommendations was proposed. This was done with the goal of improving the management and efficiency of the system. These suggestions are listed in the table below:

Table 1.2.1: Table displaying the different alternatives of energy conservation.

| RVC & Strathcona Energy Conservation Recommendations | | |
|---|---|---|
| **ECR #** | **ECR Title** | **Suggestions** |
| **1** | Steam Network and Metering | Independently meter RVC West and Roscoe to track steam usage |
| | | Install meter for energy tracking to pursue an analysis by end-use |
| | | Seasonal adjustment / new meters adapted for summer monhts |
| | | Billing structure needs to be revised, second hot water credit is to be granted to RVC |
| **2** | Domestic Hot Water Network | East Music should produce its own water using electrical or natural gas heaters |
| | | Middle Music should produce its own water using electrical or natural gas heaters |
| | | Cafeteria could produce its own water using electrical or natural gas heaters |
| **3** | Lighting | Some fixtures (T12, T8, Incandescent bulbs) are outdated and should be replaced |

## 2. Design 3: Overview

### 2.1 Objectives

In regards to the course outline provided for Design 2 and Design 3, students are required to follow the engineering design cycle. This procedure is divided into two phases, each of which corresponds to the curriculum of their respective courses. As described above, Design 2 was dedicated to creating a problem statement, identifying the criteria/constraints of the project and selecting possible solutions. The completion of the design cycle will be the focus of Design 3, it includes the selection of appropriate solutions to redefine the scope of the project as well as to construct a prototype, test the chosen solution and communicate it. However, projects do not always fit into this cycle as in the case of an energy audit, the prototype and constructing steps become difficult to perform. As such, the focus of the team was directed to the development and selection of solutions using a modelling approach to replace the prototyping step.

In the context of the RVC energy audit, the primary objective was the design of solutions that would increase the energy efficiency of the residence. As a result of the Design 2 survey, McGill Residences Facilities and Building Operations communicated their desire of retrofitting the hot domestic water network and lighting system. Moreover, they also expressed interest towards comparing solutions using different energy sources. Due to current financial circumstances and the environmental stance of the MEP, the design costs and energy savings were primary considerations of the project. With the understanding that the two main areas to focus were the piping network and the lighting system, a consensus was reached between McGill Residences Facilities and our team to consider two main solutions for each. With regards to piping, the first solution was to involve a network only relying on electric or natural gas heaters to supply the domestic hot water. The second solutions would involve re-working the network so as to couple steam with, again, electrical or gas heaters to provide hot domestic water. As for lighting, the two alternatives each involved the replacement of the currently installed T12 fixtures and incandescent light bulbs with more modern alternatives such as T5 or LED.

## 2.2 Analysis of current network

### 2.2.1 Current Domestic Hot Water Network

The complex's domestic hot water network originates in VB16-A, RVC West's mechanical room. The network supplies the entirety of RVC West and the Middle and East Music buildings, as well as RVC's cafeteria, which is located in the basement of the Middle Music building. The network immediately splits into two separate lines, a 4" and 2" line, both of which reduce down to a 0.75" shared direct return line.

- 4" line: Refers to the pipe circulating from RVC West to the end of east music. The pipe provides hot water to the front of the cafeteria (dishwashing room), Strathcona concert hall, and Middle and East music buildings.
- 2" line: Refers to the pipe circulating from RVC West to the rear cafeteria. The pipe provides hot water to RVC west, Middle music and the rear cafeteria (kitchen area).

The pipe is oversized due to the Music building's history as a nurse's residence. Residential buildings typically have higher hot water demand to provide for showers and hygienic use. Since the buildings were converted to educational purposes in 1971, their hot water requirements have been drastically reduced, leaving RVC's cafeteria as the predominant source of hot water demand outside of the residence. Both lines undergo several changes in diameter over the course of the network before reaching the 0.75". Figure 3.2.1 depicts the current network as a whole, where color corresponds to pipe diameter.


*Figure 2.2.1.1: current domestic hot water network by diameter*

In commercial buildings such as RVC West, a recirculating water network is often implemented to ensure that hot water is available at all points throughout the network. It is suggested that any domestic hot water network spanning over 30m in length implement a recirculating line (ASHRAE, 2003). RVC's domestic hot water network was constructed with a direct return line (Figure 2.2.1.2). Direct return networks encourage the "first in first out" (FIFO) principal, in which water entering the first takeoff of the network, will be the first to again enter the return line at the closest point to the heat exchanger. Due to cumulative head losses, the inlet pressure at the furthest takeoffs will be reduced in comparison to that of the closest takeoffs, resulting in poor circulation in hydraulically remote locations on the network. As was the case in RVC, direct return systems are often selected for their lower instillation costs, in comparison to the additional piping required in a reverse return system.

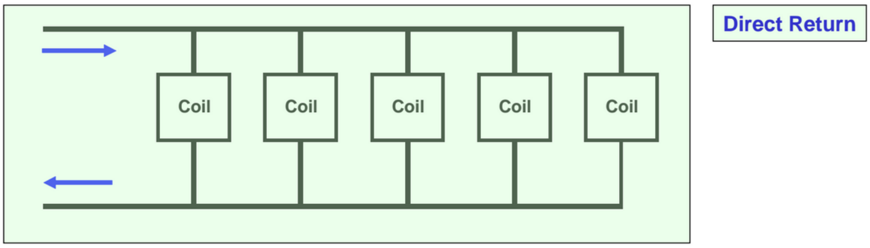



*Figure 2.2.1.2: Direct Return line of RVC's domestic hot water network*

The Leslie Heat exchanger in VB16-A is capable of producing up to 60 gallons of hot water per minute at a maximum capacity of 4.4˚C to 60˚C. Water from the return line passes through an AMOT thermostatic valve and is directed back through the heat exchanger if it is below 49 °C, otherwise it recirculates back throughout the network. Makeup water is provided to the system directly from the city's groundwater supply, and thus can vary in temperature from 4.4˚C to 15.6˚C depending on the season. It will be assumed that this makeup water is supplied at an average of 10.2˚C throughout the year.

Over the course of BREE 490's level I ASHRAE energy audit, several issues were identified with the network as a whole, including lack of metering, poor circulation, and high-energy demand due to poor efficiency. In assessing efficiency of the network, the distinction must be made between heat lost in circulation, and heat loss due to demand.

Heat lost in circulation is a constant heat loss occurring throughout the network, and is directly related to the structure of the network, pipe diameter, length and insulation quantity and quality. This heat loss can be equated to the flow rate through the Leslie heat exchanger, and the inflow and outflow temperatures of that flow. Heat loss due to demand can be equated to the volume of water removed from the system due to demand, and consequently the energy required to heat the same volume of makeup water that is being fed back into the system from the city's groundwater supply. Although makeup water and recirculating water are mixed before entering the Leslie, their respective flow rates and temperatures will be separated for the purpose of this project.

### 2.2.2 Simulation

Due to a lack of flow meters and temperature sensors available within the current network, Matlab and COMSOL simulations (Appendix C) were developed in an effort to better assess the circulation of water throughout the existing domestic hot water network. The models were constructed with the intention of investigating heat loss over the length of the network, and flow rate as a function of initial pressure, pressure losses due to frictional forces along the pipe, fittings, and elevation.

COMSOL's pipe flow module was used to provide an accurate means by which to model fluid mechanics, and heat transfer within the pipe. Pipe coordinates were uploaded to a 3D COMSOL environment including the various elevation changes occurring throughout the network. In calculating pressure losses, a volumetric flow rate for the system as a whole, and resulting velocity was assumed for each diameter of pipe, which was necessary in supplying COMSOL with initial and final pressure parameters. Considerations for head loss included:

- Pipe Length and Diameter
- Reynolds's Number
- Pipe Junctions (ASHRAE K-coefficients)
    - 90˚ Elbows
    - T-Junctions
    - Return Bends
- Elevation within the COMSOL environment

Table 2.2.2.1: Table displaying the head loss and pressure loss over the length of the various pipe sizes

| DIAMETER (INCH) | LENGTH (M) | HEAD LOSS (M) | PRESSURE LOSS (KPA) |
|---|---|---|---|
| **4** | 121.9 | 0.01 | 0.049 |
| **2** | 58.8 | 0.02 | 0.151 |
| **1.85** | 48.4 | 0.02 | 0.804 |
| **1.5** | 50.3 | 0.05 | 1.04 |
| **1** | 28.2 | 0.11 | 0.34 |
| **0.75** | 304 | 4.37 | 74.2 |
| | 611.6 | 4.58 | 76.584 |

Table 2.2.2.1 suggests that 95% of total pressure loss occurs within the 304 meters of 0.75" return pipe. This head loss is due to an increase in water velocity through smaller diameter piping, contributing to higher turbulence and therefore frictional and junction losses. In a system with a lesser volumetric flow rate, or smaller ratio between inflow and outflow diameter, this pressure loss would be less drastic, as well as more evenly distributed amongst decreasing pipe diameters. Temperature loss was calculated entirely within the COMSOL environment, with the only input parameter being the 60˚C outflow temperature from the Leslie.

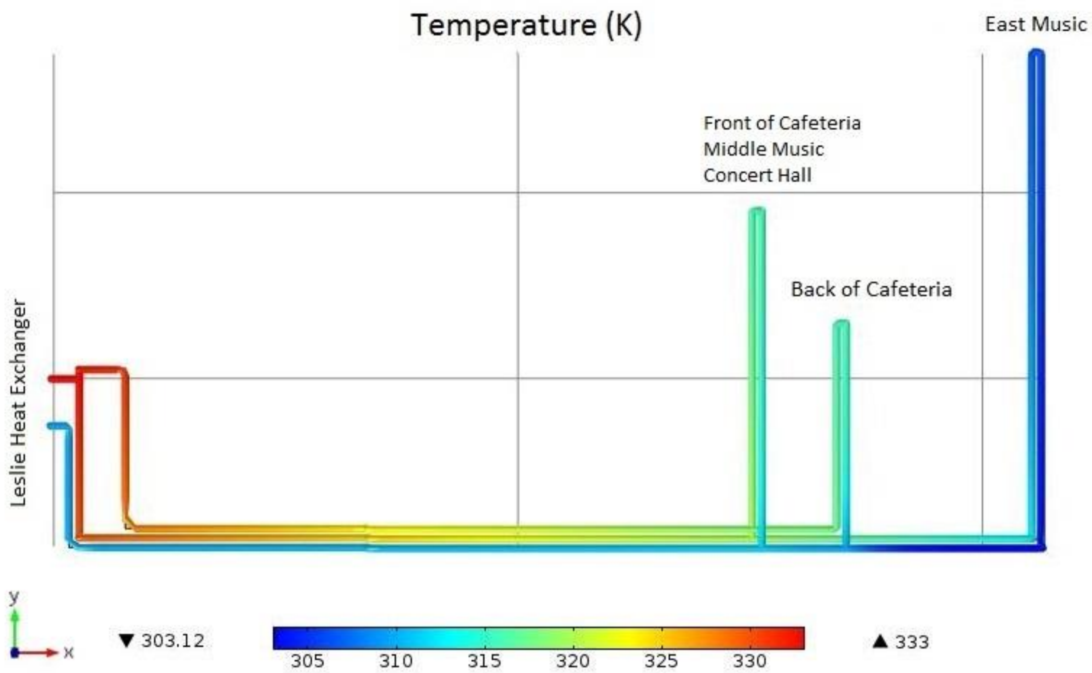



*Figure 2.2.2.1: Comsol graph displaying the temperature loss over the length of the pipes*

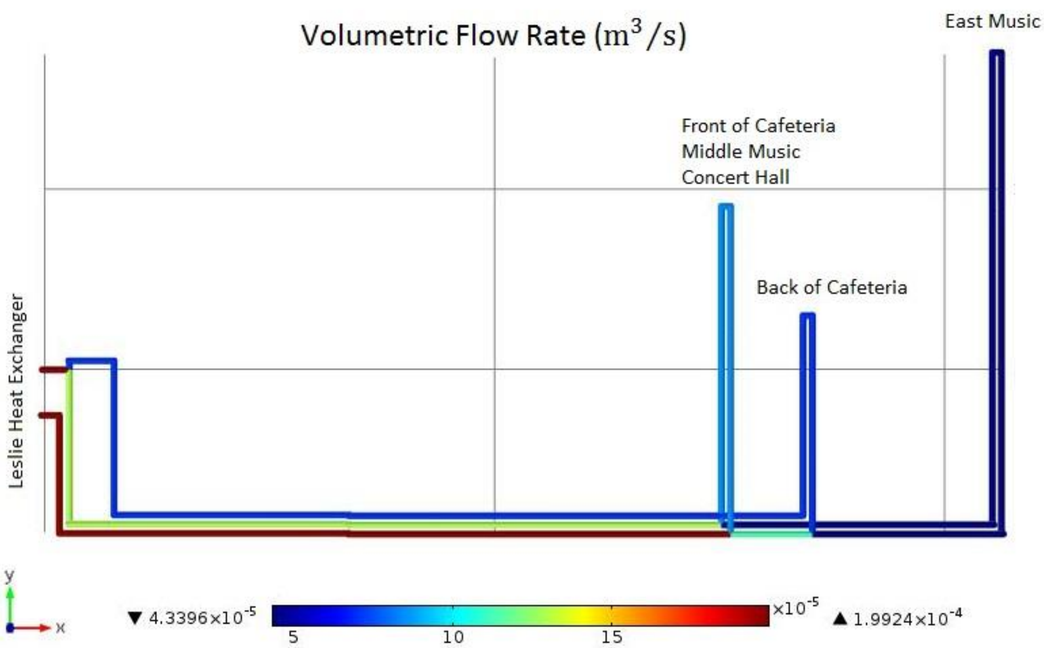



*Figure 2.2.2.2: Comsol graph displaying the volumetric flow rate over the length of the pipes*

By combining the temperature and volumetric flow data taken from figures 2.2.2.1 and (2.2.2.2), It is possible to determine the total water flowing through the Leslie under periods of no demand as approximately 17 $m^3$ per day, while undergoing a temperature increase from 38˚C to 60˚C. Daily energy loss from circulation through the network can therefore be approximated through equation 2.2.2.1:

Equation 2.2.2.1:

$$Q = mc\Delta T$$

$$Q = 17m^3 \times \frac{1000kg}{m^3} \times 4.181\frac{kJ}{kgK}\left(333K - 311K\right)$$

This results in an energy demand of 1.564 GJ per day, to circulate water throughout the network. A similar approach can be taken in order to determine energy demand required to heat makeup water as a result of demand on a daily basis. From tables 3.3.3.2 and 3.3.3.3, it can be determined that daily water use of the Middle music building, East music building, and Cafeteria are, 2592 L, 2592 L, and 14636 L respectively. This leads to a total daily water demand of 19.82 $m^3$ of water, where all makeup water must be heated from an average of 10.2˚C, to 60˚C. Therefore daily energy demand due to makeup demand throughout the network can be approximated through equation 2.2.2.2:

Equation 2.2.2.2:

$$Q = mc\Delta T$$

$$Q = 19.82m^3 \times \frac{1000kg}{m^3} \times 4.181\frac{kJ}{kgK}\left(333K - 283.2K\right)$$

This results in an energy demand of 4.127 GJ per day, to heat the makeup water caused by demand throughout the network. By comparing the results of equation 2.2.2.1 and 2.2.2.2, it can be estimated that the energy lost in circulation is 27.5% of the energy required by demand, which is a substantial portion of total energy required to operate the system. Energy required due to demand is expected to fluctuate with factors such as building and cafeteria occupancy, and makeup groundwater temperature.

There were several factors not taken into account by the simulation due to limitations in software and available data. One of these was the reduced effective diameter of the pipe due to mineral buildup throughout the network. In past replacements of segments of the building's domestic hot water piping, it was found that mineral buildup was extremely severe, and in many cases drastically reduced effective pipe diameter. This would further limit flow throughout the system, and provides a possible explanation for cafeteria employees having to open hot water taps for up to 15 minutes in the mornings to produce sufficiently hot water.

### 2.2.3 Current System Analysis

With the interest of redesigning the domestic hot water distribution system, hot water demand will be considered a constant parameter. Potential alternatives will attempt to increase system efficiency by minimizing the estimated 27.5% energy loss due to circulation. Therefore without considering energy used through demand, there are a number of ways to reduce the overall energy demand of the system. Therefore potential alternatives to the current network will attempt to resolve the issues of heat lost in circulation, proper metering, and adequate final outflow temperatures to ensure that no more than a maximum drop of 10˚C occurs at the furthest point on any outflow (ASHRAE 2003).

Properly insulated piping is perhaps the most direct and intuitive means by which to decrease energy loss in circulation. An ideal circulating system would have negligible heat loss in circulation due to excellent insulation, where the majority of energy demand would be a result of heating makeup water to compensate for demand. A sample area taken from a 4” section of piping was found to have 1” of asbestos insulation, which falls short of the ASHRAE recommended standards of 1.5” of insulation for a 4” pipe at an operating temperature of 60˚C (ASHRAE 2012).

Greater pipe diameter will result in increased natural convection due to increased surface area, which ultimately leads to greater energy losses. To a certain extent, low diameter piping can actually act as an insulator. Reducing pipe diameter and length also results in an overall reduction in volume of water in circulation, which ultimately leads to a reduction in total energy loss in the system. Having a high volume of water in circulation for the network was once necessary given Strathcona’s history as a residence, however with its current expected demand, the volume of water currently in circulation results in large and unnecessary energy losses throughout the system.

Flow rate impacts system efficiency in an entirely different way. In the case of RVC’s domestic hot water network, increasing flow rate through the network it is possible to solve the issue of hydraulically remote regions of the network not being provided adequately hot water, and therefore maintain a higher average water temperature throughout the system. However it is likely that overall energy demand has increased. With an ambient air temperature of 21˚C, significantly more energy is lost from a pipe carrying water at 60˚C, than from a pipe at 30˚C (Appendix C). Therefore the current system has a reduced energy demand in circulation due to the large temperature drop occurring over the length of the pipe, however this comes at the sacrifice of remote regions of piping not receiving adequately hot water.

A final consideration in the design of potential alternatives will be in the implementation of alternative energy sources. The three options that will be compared are the current Leslie heat exchanger system, which is provided steam through McGill Universities Utilities and Energy Management, which is in turn provided natural gas through Gaz Métropolitaine. The second and third options are individual natural gas and electricity powered domestic hot water tanks, which will be analyzed and compared in term of both cost and efficiency.

Due to the higher energy demand required in heating makeup water in comparison to the energy lost in circulation, this paper will use demand as the driving factor in the assessment of all alternative solutions to the current network, and heat lost in circulation will be neglected. It can be assumed that due to the reductions in network size suggested through retrofitting in section 3, heat loss due to circulation will be drastically reduced, and the primary area of energy demand will be in heating makeup water as a result of demand.

## 3. Design 3: Hot Domestic Water Network Retrofitting

### 3.1 Design procedures

Before describing with details the two alternative proposed, this section will describe the design procedures used. Computations for sizing and selection of appropriate utilities are based on ASHRAE standards and are uniform in both design considerations. The procedure is discussed in the sections below.

#### 3.1.1 Pump sizing

The following method suggested by Werden and Spielvogel (G. Werden, 1969) and Dunn et al. (T.Z. Dunn, 1959) returns the pump capacity as a function of an allowable heat loss for large systems. The procedure consists of approximating the total heat loss over the length of the water supply and return lines. Using the following equation, the pump capacity can approximated (ASHRAE, 2003):

Equation 3.1.1.1: Pump capacity / Ideal Flow

$$Q = \frac{q}{\rho c_p \Delta t} \quad \textit{where,}$$

*Q: pump capacity / design flow (L/s)*
*q: heat loss in (W) = 60 W/m · Length of pipe (m)*
*ρ: water density (kg/L) = 0.99 kg/L*
*$c_p$: specific heat of water (J/Kg · K) = 4180 J/(Kg · K)*
*Δt: allowable temperature drop (K) = 1 K*

Pump capacity reflects the required flow rate within the network. In order to select a recirculator, the pressure loss in the pipe (also known as head loss) must be computed. The pressure drop within pipes incorporates both the drop caused by fluid friction in Newtonian fluids and the pressure drops due to fittings. Note that the following equations obtained from the ASHRAE handbook for pipe sizing were adjusted to SI units for the pressure and head drop (ASHRAE, 2009). Using these equations a pump can be selected in function of the values obtained for the loss in pressure within the pipes and the desired flow rate. The solutions presented in this project all use in-line circulators manufactured by Armstrong. The specific models were selected using a graph (figure 3.1.1.1) displaying the ratings of each of their products.

Equation 3.1.1.2: Pressure drop/ Head Loss

$$Re = \frac{DV\rho}{\mu} \quad \textit{where,}$$

*Re: Reynolds Number*

*D: pipe diameter (m)*

*V: average fluid velocity (m/s) = Q / Surface Area of Pipe*

*μ: dynamic viscosity of fluid (Pa·s)* = $6.54 \cdot 10^{-4}\ Pa \cdot s$

Equation 3.1.1.3: Darcy Friction Factor

$$f = \frac{64}{Re} \quad \text{where,}$$

*Re: Reynolds Number*

*f: Darcy Friction Factor*

Equation 3.1.1.4: Darcy-Weisbach equation

$$\Delta h = f \cdot \frac{L}{D} \cdot \frac{V}{2 \cdot g}$$

$$\Delta p = f \cdot \frac{L}{D} \cdot \frac{\rho V^2}{2} \quad \textit{where,}$$

*Δp: pressure loss (Pa)*

*Δh: head loss (m)*

*G: acceleration of gravity* $(m/s^2) = 9.81\ m/s^2$

Equation 3.1.1.5: Valve and Fitting Losses

$$\Delta h = K \cdot \frac{V^2}{2 \cdot g}$$

$$\Delta h = k \cdot \frac{\rho}{g} \cdot \frac{V^2}{2} \quad \textit{where,}$$

| *K: 90 Bend* | *K: Tees* | *K: Return Bend* |
|---|---|---|
| *0.38* | *1.8* | *1* |

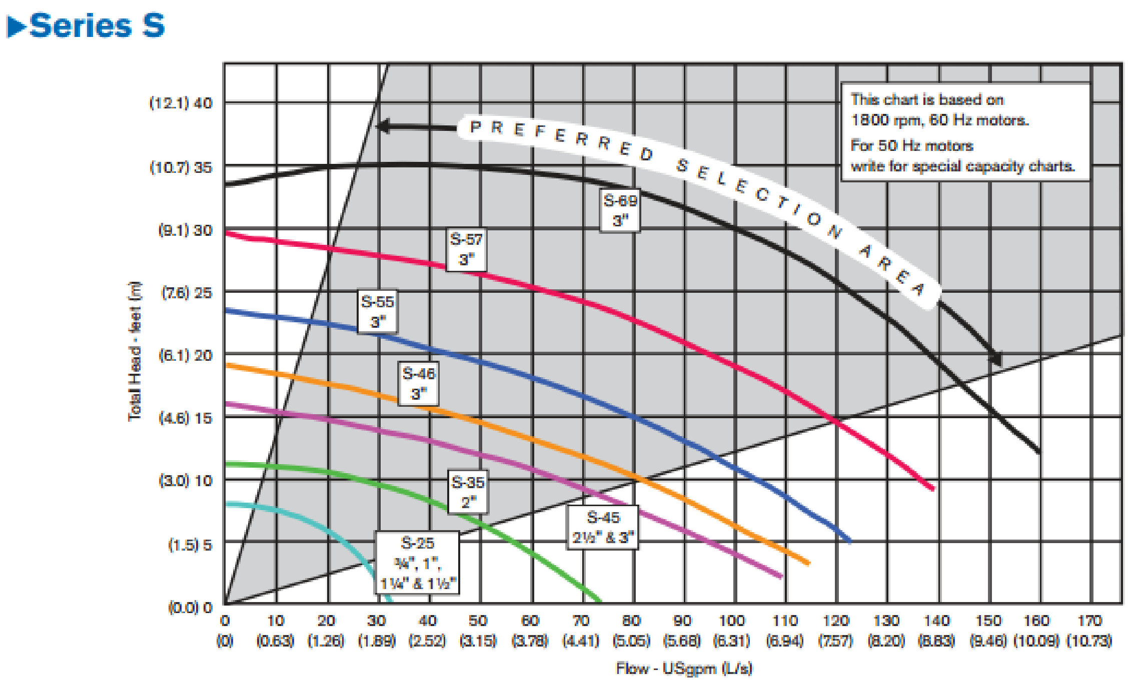



*Figure 3.1.1.1: Armstrong manufacturer graph displaying the rating of their products*

### 3.1.2: Water tank types and sizing

Properly sizing water tanks is dependent on two variables: recovery rate and storage capacity. Recovery rate is defined as the volume of hot water that the heater can continually provide per unit of time. Storage capacity is simply the maximum amount of water an individual water heater can store.

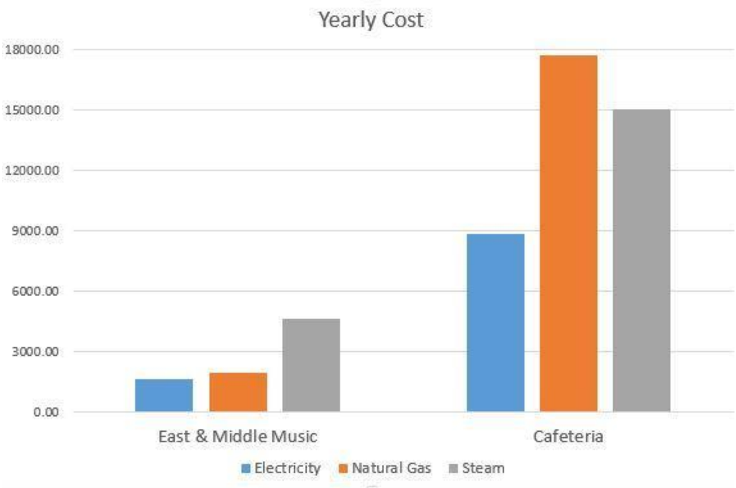



*Figure 3.1.2.1: Theoretical yearly cost (CAN$) associated with water consumptions in the three main areas.*

In addition to these two criteria, the design considerations include the energy source and the desired temperature of outgoing hot water. In the case of this project, the most specific outgoing temperature that could be obtained as being necessary was the inlet temperature of the dishwashing machine in the Cafeteria at 49°C (120°F). Considering an inlet temperature of 10C (50°F) going in the heater, a temperature change of 39C (70°F) was used for all calculations. Comparing gas heaters with electric heaters for different scenarios revealed that the use of electricity was preferred as it was more economical both in monetary and energy terms. Figure 3.1.2.1 displays the yearly cost associated with the consumption of water in the East and Middle music buildings and cafeteria. In this figure, Electrical and gas heaters were compared using electricity to natural gas equivalencies provided by the manufacturer (Rheem, 2013). The price of electricity used is 0.0304$/kWh, 10.57$/GJ for gas and $0.2342/lb of steam.

Determining the size and recovery rate of electric heaters was done using table data provided in the ASHRAE handbook for service water heating (ASHRAE, 2003). Table are available for various types of building of building uses. In regards to the energy audit of RVC, the East and Middle music buildings were designated as office buildings while the cafeteria qualified as a type A food service. Figure 3.1.2.2 illustrates the tables used for the design of the two proposed solutions. Calculations for sizing assume that 70% of the hot water in each storage tank can be designated as usable.

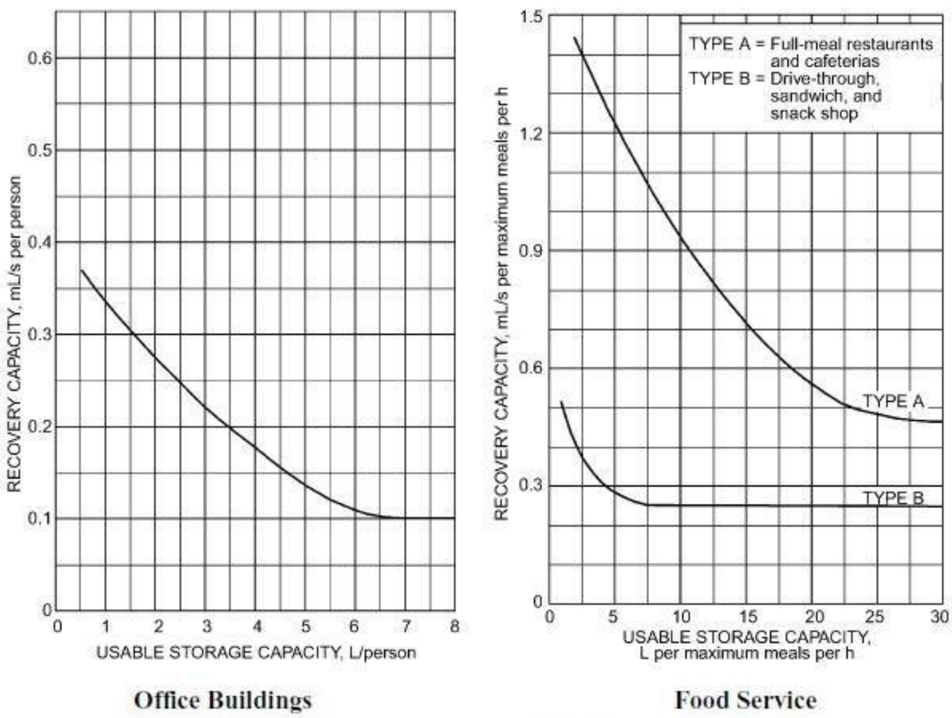



*Figure 3.1.2.2: Graphs illustrating the recovery and usable storage capacity for Office Buildings and Food Service Buildings*

### 3.1.3 Risk assessment: Asbestos removal

Investigations in the building revealed that the insulation for most of the pipes in RVC and Strathcona was done using asbestos. This is a main limitation with regards to the investment costs and retrofitting opportunities. Asbestos is a dangerous material which releases small particles in the air when manipulated. If the dust is inhaled severe health consequences can occur. Asbestos is considered to be hazardous if the particle concentration exceeds 0.1% (Quebec, 2014). Modifying the pipe network in buildings would involve manipulating asbestos. As such precautions must be taken to guarantee the safety of workers, employees and students (Canadian Environmental Law Association,2012).

Upon contacting *Aire D3 Inc* (www.enlevementamiante.com), a local contractor specialized in asbestos removal, the associated cost to remove pipe insulation was estimated. What was found was that two types of asbestos are commonly used: Chrysotile asbestos, which is generally applied for domestic water network at fairly low temperatures (below 100°C) and amosite asbestos which is required to insulate networks at higher temperatures. Chrysotile asbestos is easier and cheaper to remove as it does not involve depressurizing the building to remove the hazardous particles which is the case with amosite asbestos. According to the contractor, water pipes circulating domestic water in RVC and Strathcona were most likely insulated with chrysotile asbestos. However, further investigation is required to assess which type of asbestos is truly present in these buildings. Table 3.1.3.1, provides price approximations from *Aire D3 Inc* for both insulations types. Prices can differ by a factor of 10 between chrysotile and amosite asbestos. In either case, costs associated to the removal and retrofitting of pipe insulation are high, thus favoring the re-use of existing pipes.

Table 3.1.3.1: Price comparison between the two types of asbestos insulation removal

| | **Chrysotile asbestos** | **Amosite asbestos** |
|---|---|---|
| **Required Time** | 22 days with 3 employees | Hard to estimate (1-2 months) |
| **Prices** | 25$ per 0.3 m | Hard to estimate |
| **Prices for 614 m** | Minimum of 50,278$ | Hard to estimate (Minimum of 500 000$) |

### 3.2 Option 1

### 3.2.1 Overview

In this design Middle Music and East Music wings have been entirely separated from the original hot water network (4'' pipe), and three independent loops have been created to deliver the hot water. This option is shown in detail in Figure 3.2.1.1


*Figure 3.2.1.1: Option 1 piping loops*

These three loops will individually be referred to as the Cafeteria loop, the Middle Music loop (which also feeds the Concert Hall), and the East Music loop. The aim of this design was to completely remove the oversized 4” pipe, which is cut between the buildings of RVC West and Middle Music. This option would require a total of 116m (383ft) of asbestos removal.

### 3.2.2 Design Parameters

This problem was approached using the design procedure described in section 3.1. For this option, it was deemed important to keep as much existing piping as possible, in order to reduce investment costs. As such, the first step consisted of rearranging the current network accordingly.

<u>Table 3.2.2.1:</u> Table displays the estimated length and diameters of existing and new pipes that are required for each loops:

| Option 1 | Pipe Diameter (in) | Pipe Length (m) | New Pipe (m) | Total Length (m) | Ideal Flow Rate (m3/s) | Pressure Loss (kPa) |
|---|---|---|---|---|---|---|
| Cafeteria Loop | 1.5" | 0 | 34.7 | 118 | 6.89E-04 | 20.19 |
| | 1" | 24.2 | 0 | | | |
| | 3/4" | 24.2 | 34.7 | | | |
| Middle Music Loop | 2" | 33.7 | 0 | 156 | 1.00E-03 | 51.09 |
| | 1.5" | 44.1 | 9.4 | | | |
| | 3/4" | 78.4 | 8.8 | | | |
| East Music Loop | 4" | 21.7 | 0 | 125.7 | 7.00E-04 | 19.05 |
| | 2" | 12 | 0 | | | |
| | 1.5" | 12 | 5 | | | |
| | 1" | 12 | 0 | | | |
| | 3/4" | 58 | 5 | | | |

As can be seen in Table 3.3.2.1, the Cafeteria loop requires the most additional piping. The new 1.5” pipe and associated return line are required to connect the rear of the cafeteria and the dishwasher area. The Middle and East Music loops only need a limited amount of new piping. They require just enough to make the connection to their corresponding heaters. Using the equations of section 3.1.1, flow rates were optimized to diminish heat and pressure losses.

ASHRAE guidelines were used to estimate the required size of the water heaters. The same procedure was used for all three loops. It was assumed here that the East and Music buildings host the same amount of students daily and hence have the same water consumption. The design considerations for both loops are therefore identical. Moreover the buildings were assumed to fall under the category of offices in terms of hot water demand, and Figure 3.1.2.2 was again used. Therefore it was estimated that the heaters have the capacity to sustain 1.5 liters of hot water for each of 200 persons on a daily basis.

Table 3.2.2.2: Table showing the final recovery rate and water tank required:

| Option 1 | Number of person | Usable Storage Capacity (L/person) | Recovery Capacity per person (mL/s) | Required Storage (L) | Required Storage (Gal) | Total Recovery (L/hour) | Size of heaters (gal) | Number of heaters | Daily Water Use (L) |
|---|---|---|---|---|---|---|---|---|---|
| Middle Music Loop | 200 | 1.5 | 0.3 | 417 | 110 | 216 | 111 | 1 | 2592 |
| East Music Loop | 200 | 1.5 | 0.3 | 417 | 110 | 216 | 111 | 1 | 2592 |

Considering the cafeteria loop, the heater sizing was achieved based on the busiest period of the day. Using Figure 3.1.2.2, the maximum amount of meals served by hour was found to be 242, and a required storage per meal of 2.5 L. Table 3.2.2.3, show the final recovery rate and water tank required.

Table 3.2.2.3: Table showing the final recovery rate and water tank required for the Cafeteria loop

| Option 1 | Max number of meals per hour | Usable Storage Capacity per hour (L/meal) | Recovery Capacity per meal per hour (mL/s) | Required Storage (L) | Required Storage (Gal) | Total Recovery (L/hour) | Size of heaters (gal) | Number of heaters | Daily Water use (L) |
|---|---|---|---|---|---|---|---|---|---|
| Cafeteria | 242 | 2.5 | 1.4 | 864 | 228 | 1220 | 120 | 2 | 14636 |

Table 3.2.2.2 and 3.2.2.3, indicate that a water heater with a storage capacity of at least 111 gallons is required for the east and middle music loop and a heater exceeding 222 gallons for the cafeteria. It was determined that this option will imply the installation of one Rheem-Ruud Heavy Duty 120 gallons in each music buildings and two in the cafeteria (Rheem, 2013). Moreover, pump requirements are more or less the same, using values in Table 3.2.2.1) as well as Figure 3.1.1.1 the S-25 in-line circulator was then selected as the preferred pump.

### 3.2.3 Model Results

A model was built in COMSOL using the isothermal pipe flow module to analyze the performance of the designed loops. Parameters and initial condition used in the simulations are listed in Appendix A.3. Below is the result of the analysis and the specific temperature profile along each loop.

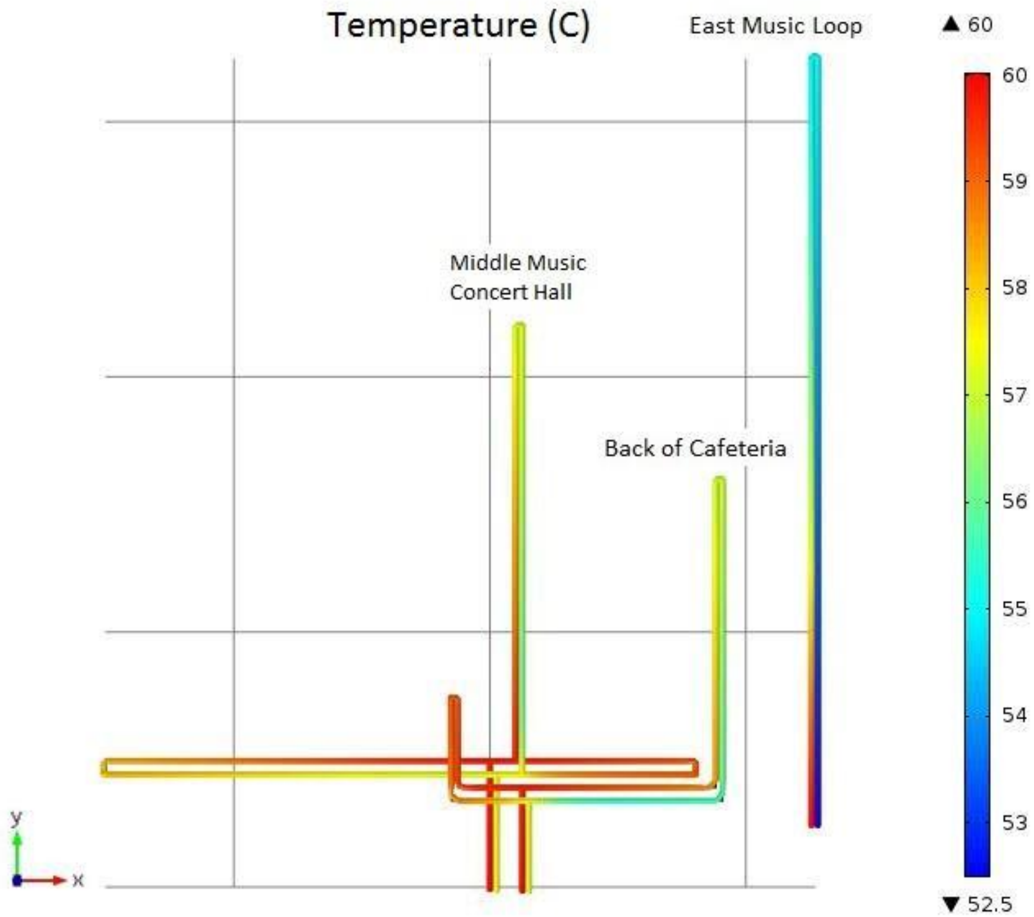



*Figure 3.2.3.1: Comsol Model of Option 1 Temperature profile*

The results show overall decrease in temperatures of 3°C in the Middle Music loop, 5°C in the Cafeteria loop and 8°C for East Music loop. Steady state volumetric flow rate was also modeled Appendix C. Having the three loops independent of each other addresses several problems. By metering each loop individually, the billing process is accurate and standardized throughout the network. Each of the loops draws and uses hot water from its own demand only, eliminating the circulation of water to unmetered areas. The ability to service, modify, or fine-tune a loop without disturbing other zones, enabling the system to be much more efficient.

**3.2.4: Energy savings, Costs and return investment**

To calculate the cost of implementation of such a design, a list of materials was made for each loop (Appendix A.4). Costs and savings for each loop were added to obtain a final cost of implementation and a final savings of implementation. A summary of each loop cost is shown below.

Table 3.2.4.1: Cost Summary of Option 1

| **Option 1** | | |
|---|---|---|
| Loop | Cost | Annual Savings |
| Cafeteria | $ 30,088.00 | $ 18,018 |
| Middle Music | $ 21,495.67 | $ 2,981 |
| East Music | $ 29,741.00 | $ 2,603 |
| Total | $ 81,324.67 | $ 23,602 |
| Payback Period (yr) | | 3.4 |

The calculations for the savings were done by estimating the cost of steam and electricity required to heat the amount of water demanded, and then subtracted one to the other. Table 3.2.4.2 below shows the breakdown of these calculations.

Table 3.2.4.2: Calculation of Cost breakdown

| Option 1 | Electrical requirements (kW) | Natural Gas requirements (Btu/h) | Daily operation time (hour) | Electrical Yearly costs ($) | Naural Gas Yearly Cost ($) | Steam Yearly Cost ($) |
|---|---|---|---|---|---|---|
| **Cafeteria Loop** | 60.06 | 102400 | 12 | 7997 | 9866 | 25100 |
| **Middle Music Loop** | 12.06 | 40000 | 12 | 1584 | 1927 | 4589 |
| **East Music Loop** | 12.06 | 40000 | 12 | 1584 | 1927 | 4589 |
| | | | Total | 11165 | 13720 | 66671 |

It is noteworthy to say that for all calculations, a time period of 365 days was taken. However, days in which the loops do not draw water, especially in the case for the Cafeteria, would lead to reduced savings which would increase the payback period. The value of BTU/hr was used as the base estimate to calculate the cost of gas (Rheem, 2013)

### 3.3 Option 2

#### 3.3.1 Overview

The second option proposed in this report involves coupling water heaters with the current system supplied by steam. This design involves feeding the cafeteria and the middle music building using the existing Leslie heat exchanger in VB16-A, while supplying water heaters for the east music buildings. In other terms, both the cafeteria and the middle music building will be dependent from RVC's hot domestic water production and the east music building will be independent ((Figure 3.3.1.1). This consideration aimed to explore the effect of detaching the East music building from the rest of the network, thereby improving network circulation and overall temperature profile. Moreover, this option solicits removing the entire 4" pipe from the Leslie, which was a main contributor to heat lost in circulation. As a result, the front of the cafeteria and the concert hall which used to be fed with the 4" network will be connected to the existing 2" pipe feeding the back of the cafeteria (Appendix B).

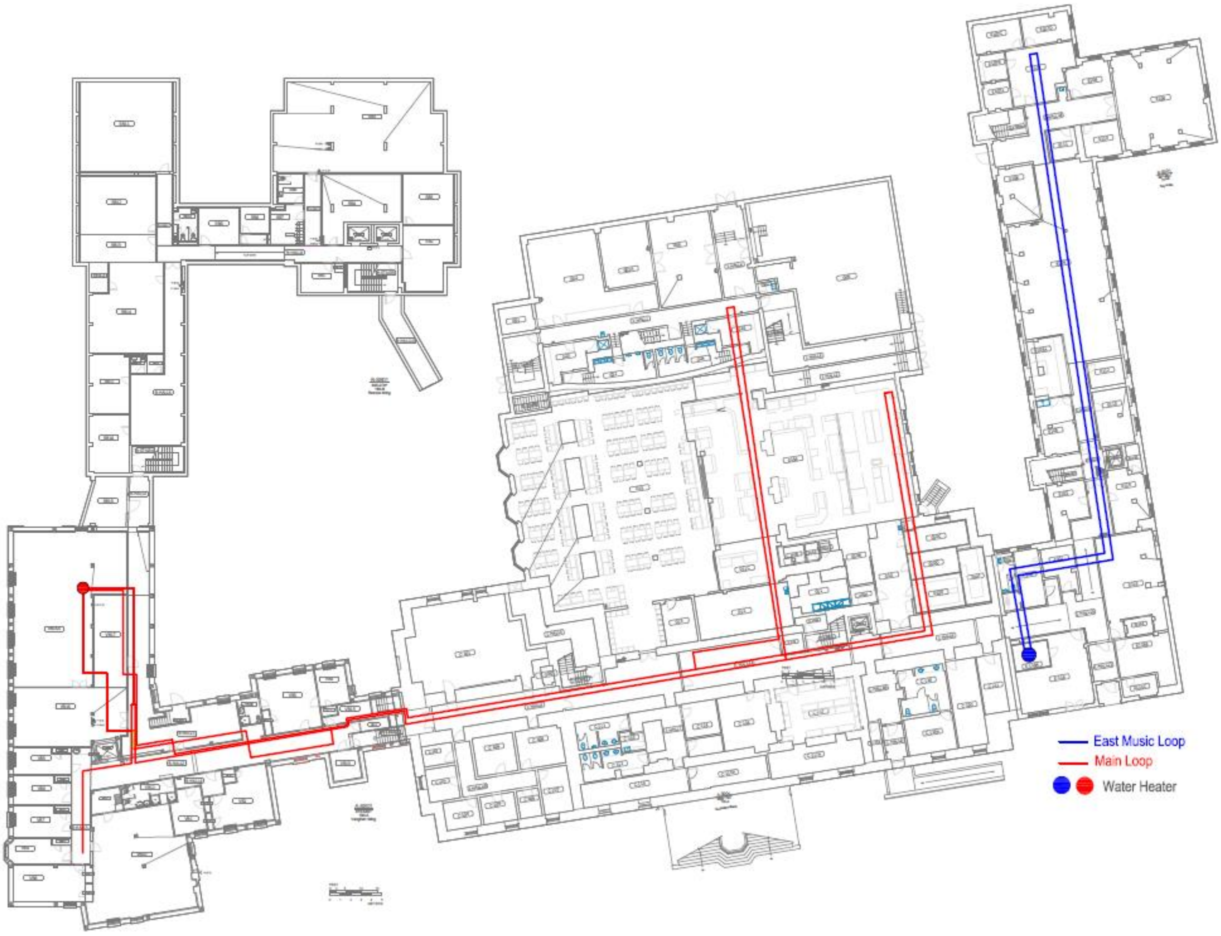



*Figure 3.3.1.1: Option 2 loops*

### 3.3.2 Design Parameters

The problem was approached using the design procedure described in the above section. To reduce investment costs, it was decided that keeping the majority of existing pipe was necessary. The first step consisted of rearranging the current network accordingly.

Table 3.3.2.1: Table depicting the estimated length and diameters of existing and new pipes required:

| Option 2 | Pipe Diameter (in) | Existing Pipe (m) | New Pipe (m) | Total Length (m) | Ideal Flow Rate (m3/s) | Pressure Loss (kPa) |
|---|---|---|---|---|---|---|
| Middle Music / Cafeteria Loop | 2" | 85.97 | 5 | 330 | 1.94E-03 | 30.75 |
| | 1.5" | 50.3 | 0 | | | |
| | 1" | 23.63 | 0 | | | |
| | 3/4" | 164.9 | 0 | | | |
| East Music Loop | 4" | 21.7 | 0 | 125.7 | 7.00E-04 | 19.05 |
| | 2" | 12 | 0 | | | |
| | 1.5" | 12 | 5 | | | |
| | 1" | 12 | 0 | | | |
| | 3/4" | 58 | 5 | | | |

In regards to the middle music and cafeteria loop, only 5 meters of new pipe is required to connect the front of the cafeteria (this segment is currently supplied by the 4” pipe) to the 2” pipe feeding the rear cafeteria. Similarly to the first option, 10 meters of new pipe are required to connect the water heater to the existing pipe network. Using the equation 3.1.1.1, flow rates were optimized to diminish temperature drop, as well as the associated pressure losses.

The size of the water tank required to heat water for the consumption of the east music building was estimated identically to option 1 Figure 3.1.2.2 shows the final recovery rate and water tank required:

Table 3.3.2.2: Table showing the final recovery rate and water tank required:

| **Option 2** | **Number of person** | **Usable Storage Capacity (L/person)** | **Recovery Capacity per person (mL/s)** | **Required Storage (L)** | **Required Storage (Gal)** | **Total Recovery (L/hour)** | **Size of heaters (gal)** | **Number of heaters** | **Daily Water use (L)** |
|---|---|---|---|---|---|---|---|---|---|
| **East Music Loop** | 200 | 1.5 | 0.3 | 417 | 110 | 216 | 111 | 1 | 2592 |

Many heaters satisfy the above characteristics, however the Rheem-Ruud Heavy Duty 120 gallons (Rheem, 2013) was selected for further energy consumption calculations. Using Figure 3.1.1.1, the S-25 in-line circulator has adequate specifications to support the required flow rates. Moreover the pump has a low wattage (60 W), which will have a minimal effect on energy consumption. A comparison between both electrical and natural gas requirements and the equivalent amount of steam is conveyed in Table 3.3.2.3:

Table 3.3.2.3: Price comparison between natural gas and electricity

| **Option 2** | **Electrical requirements (kW)** | **Natural Gas requirements (Btu/h)** | **Daily operation time (hour)** | **Electrical Yearly costs ($)** | **Natural Gas Yearly Cost ($)** | **Steam Yearly Cost ($)** |
|---|---|---|---|---|---|---|
| **East Music Loop** | 12 | 40000 | 12 | 1576 | 1927 | 4589 |

### 3.3.3 Model Results

Similarly to the first option, a model was constructed to conclude the cycle of engineering design and evaluate returned outputs. Using COMSOL, a temperature, volumetric flow rate, and pressure profiles were computed to assess the efficiency of this alternative. Figure 3.3.3.1 displays the change of temperature along the network while Appendix C.2 represents the flow rate within the pipes.

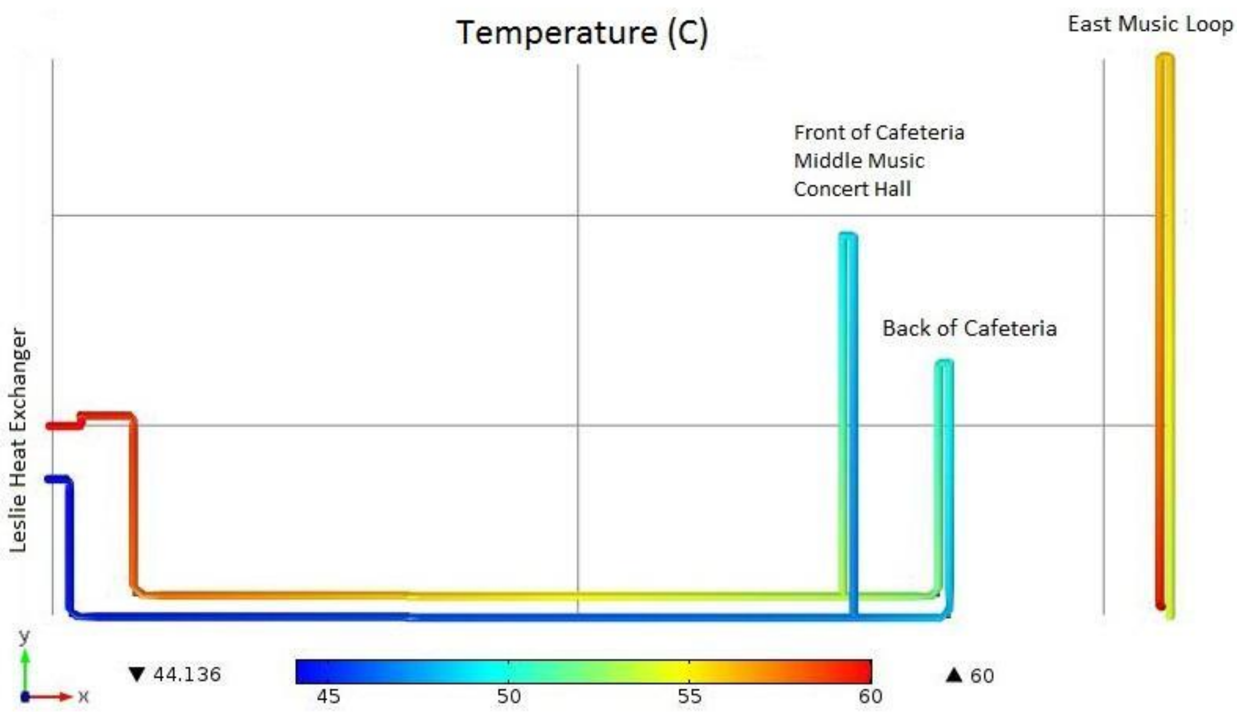



*Figure 3.3.3.1: Comsol Model of Option 2 Temperature profile*

The results obtained from COMSOL suggest that this alternative solves the temperature issue of the current system. The water temperature at the concert hall and at back of the cafeteria reaches a minimum of 48°C, thus resulting in a temperature drop of 12°C. Additionally the circulation within the network is approximately doubled when compared to the present network (Appendix C.2). Results from the east music loop are the same than option 1. This design emphasizes the inefficiency of the 4” line. Removing this pipe has a substantial effect on the flow rate within the 2”, thus considerably decreasing heat losses. Although this option solves the issues of heat loss and circulation, metering will not be entirely resolved. With option 2 it is still not possible to differentiate middle music from the cafeteria in terms of water consumption, however it would be possible to credit a portion of the Leslie’s steam demand to McGill, based on estimated demand.

### 3.3.4 Energy Savings, Costs and return investment

Similarly to Option 1 a list of materials was made to estimate the cost of this options. Although there is very little new pipe installments, the complete removal of the 4” pipe is still in place, which is the main driving costs out of the materials. The cost of this option is the same as the cost of the Middle Music loop, specifically done for that. Below is the breakdown of the cost of investment.

<u>Table 3.3.4.1:</u> Table displaying the cost and annual savings of option 2

| **Option 2** | Cost | Annual Savings |
|---|---|---|
| Middle Music | $ 21,495.67 | $ 2,981 |

Table 3.3.4.2: Table displaying the cost breakdown of Option 2

| Option 2 cost breakdown | | | |
|---|---|---|---|
| **Item** | **Price ($/unit)** | **#** | **Price ($)** |
| Hot water heaters for east music | 2000 | 1 | 2000 |
| Circulating pumps for east music | 800 | 1 | 800 |
| 90 elbows 4'' | 150 | 5 | 750 |
| 90 elbow 3/4'' | 80 | 5 | 400 |
| Tees 3/4'' | 107 | 2 | 214 |
| 2'' copper pipe (5 ft) | 119 | 1 | 119 |
| 1.5'' copper pipe (6 ft) | 113 | 1 | 113 |
| 1'' copper pipe (6ft) | 80 | 2 | 160 |
| 3/4'' copper pipe (6ft) | 55 | 2 | 110 |
| Globe valve | 80 | 1 | 80 |
| Cost of extra insulation (3ft) | 35 | 12 | 420 |
| Aebstos removal (4'' leftover) | 25 | 383 | 9575 |
| Cost of labour | | 1 | 15000 |
| Total cost of investment | | | 29741 |
| Savings | | | 2603 |
| ROI | | | 11.42499 |

**3.4 Option Comparison**

Table 3.4.1: Table showing the comparison in costs of each option.

| Comparison | | |
|---|---|---|
| | Option 1 | Option 2 |
| Cost | $ 81,325 | $ 29,741 |
| Savings | $ 23,602 | $ 2,603 |
| Payback Period (yr) | 3.4 | 11.4 |
| **Problems Solved** | | |
| Mixed Billing | ✓ | |
| Oversized piping | ✓ | ✓ |
| Mixed circulation | ✓ | |
| Adequate outflow temperature | ✓ | ✓ |

Option 1 has a very low payback period due to the high savings, most of which are a result of the Cafeteria loop. As mentioned above, Cafeteria savings would lower be if it would not operate the entire year. Option 2 has the advantage of having a much lower cost. Although it does not addresses all problems, water demand from Middle Music and the Cafeteria run on the same pipes, which keeps the billing problems unless a new meter be installed in the Cafeteria takeoff. Option 2 would still it would have a more efficient system than the current situation, with low impact on infrastructure.

## 4. Lighting

### 4.1 Current Lighting Practices

It was determined from the energy audit we conducted during the fall semester that the Royal Victoria College currently uses two primary types of fluorescent lights (Table 4.1.1):

**T8:**

The T8 fluorescent tubes are 0.6 m (2 ft) in length, with a power rating of 32 Watts and a light output of 2600 lumens. Using Equation 4.1.1, the efficacy of this light can be determined as 81 lumens/Watt:

$$Efficacy = \frac{L}{P} \qquad (1)$$

Where,
L = total light output (lumens)
P = total power (Watts)

The outer diameter of the fixture is 2.54 cm (1 inch) and is classified as having a medium bi-pin base. For this type of fixture, the average lifetime is of 30 000 hours, and the Color Rendering Index (CRI) is of 80 and up (Philips, 2014). The CRI is a quantitative measure of the ability of a light source to reveal the colors of various objects faithfully in comparison with an ideal or natural light source, and ranges from 1 to 100, with 100 being optimal (Peck et al., 2011). See Figure 4.1.1 for an image of a T8 fluorescent tube light.


*Figure 4.1.1: The T12 and T8 fluorescent light bulbs (PG&E, 2012).*

**T12:**

The T12 fluorescent tubes are 1.2 m (4 ft) in length, with a power rating of 40 Watts and a light output of 2520 lumens. The efficacy of this light can be determined as 63 lumens/Watt.

The outer diameter of the light is 3.81 cm (1.5 inch) and is classified as having a medium bi-pin base. For this type of light, the average lifetime is 24 000 hours, and the Color Rendering Index (CRI) is 80 and up (Philips, 2014). Lighting at RVC represents a significant amount of all energy costs and is described in Table 4.1.1.

Table 4.1.1 Current inventory of the different light sources of RVC.

| Lamp Type | Length (ft.) | Number of Fixtures | Total Number of Lamps | Total Wattage (kW) |
|---|---|---|---|---|
| T8 single | 2 | 148 | 148 | 4.7 |
| T8 double | 2 | 24 | 48 | 1.5 |
| T12 single | 3 | 8 | 8 | 0.2 |
| T12 single | 4 | 175 | 175 | 7 |
| T12 double | 4 | 76 | 152 | 6.1 |
| Incandescent | Bulb | 57 | 57 | 3.4 |
| CFL | Bulb | 51 | 51 | 0.7 |
| **TOTALS** | **-** | **539** | **639** | **23.7** |

Table 4.1.2: Table showing the consumption and cost estimates of the current lighting system.

| | |
|---|---|
| **Estimated Annual Electrical Consumption (kWh)** | 213,349 |
| **Estimated Annual Consumption Cost ($)** | 6,293.80 |
| **Estimated Annual Demand Cost ($)** | 3,385.80 |
| **Estimated Annual Total Cost ($)** | 9,679.60 |

### 4.2 Light Types

Lighting is responsible for approximately 20% of the energy consumption worldwide (Peck et al., 2011). According to Peck et al. (2011), it is important to move toward a new alternative for lighting with increased efficiency and reduced power consumption. When specifying lighting design, engineers are primarily concerned with cost, safety, quality of light, and reliability. The maintenance, durability, and efficiency of lighting systems are also important factors to consider. There are many shortcomings in these areas with traditional lighting systems, such as incandescent and fluorescent lights.

In a study by Peck et al. (2011), LED lighting was compared to current lighting technology. The parameters of comparison included efficacy (lumens per Watt), lifetime (hours), and CRI (Color Rendering Index). The CRI assigns each light a value from 1 to 100, based on the comparison of that electrical light to natural light. It was found that LEDs had the highest CRI (100), efficacy (up to 150 lumens per Watt), and lifetime (over 100 000 hours) when compared to nine other types of lighting technology. These included High Pressure Sodium (HPS), Low Pressure Sodium (LPS), mercury vapor, metal halide, fluorescent, compact fluorescent, incandescent, induction, and Light Emitting Plasma (LEP).

In another study by Heffernan et al. (2007), LEDs were compared to fluorescent tube lighting. Lux meters were used to measure radiant light power (in lux, or lumens/$m^2$). This unit of measurement was selected because it was representative of how humans perceive the strength of light. It was found that fluorescent tubes reach higher efficacies (approximately 85 lumens per Watt), but their 360° radiation pattern means that a large portion of the light is lost. Since LED lamps are made up of multiple "white" LEDs, it was found that multiple point sources were created. This resulted in the formation of shadow lines when small objects like books were examined under the light.

With regard to the thermal performance of light technology, a study by Qin et al. (2009) examined the heat dissipation and luminous performance of LEDs as compared to fluorescent lamps. Light measurements were carried out using a spectrocolorimeter and integrating sphere, with three types of high-brightness LEDs measured against T5 and T8 fluorescents. It was found that fluorescent lamps dissipate about 73-77% of the total lamp power as heat, while LEDs dissipate 87-90%. It was determined that LEDs are inferior to T5 fluorescent lamps in terms of energy efficacy and heat dissipation.

For this project, three different types of light sources were selected for evaluation: fluorescent (T5) and LED to replace T12 bulbs, and CFL lamps to replace incandescent bulbs. These lights were compared on the basis of luminous efficacy (lumens/Watt), lifetime (hours), CRI, cost (CAD$) and environmental waste (mg of mercury, Hg). See Table 4.2.1.

Table 4.2.1: Luminous efficacy, lifetime, CRI, cost and environmental waste were considered in the evaluation of five different light sources.

| | **T12** | **T5** | **LED** | **Incandescent** | **CFL** |
|---|---|---|---|---|---|
| **Efficacy (lumens/Watt)** | 40-100 | 40-100 | up to 150 | 5-25 | 50-75 |
| **Lifetime (hours x1000)** | 6-45 | 6-45 | 100+ | 1 | 6-15 |
| **CRI (1-100)** | 60-90 | 60-90 | 70-90 | up to 100 | 60-90 |
| **Cost (CAD)** | 2.00 - 10.00 | 4.00 - 10.00 | 20.00 -60.00 | 3.00 | 5.00 |
| **Environmental Waste (mg Hg)** | 5-10 | 5-10 | 0 | 0 | 0-5 |

Values for efficacy, lifetime, and CRI were industry averages taken from research by Peck et al. (2011), while costs were assessed for each commercially available light. According to IMERC (2008), fluorescent and compact fluorescent usually contain mercury. Fluorescents and compact fluorescents contain 5-10 mg and 0-5 mg, respectively. This is an important design consideration, since the US EPA requires fluorescent and other mercury lamps to be managed as hazardous waste.

Table 4.2.2. A Pugh Chart was used to analyze the various lighting options, with respect to the fluorescents that are currently used at the RVC.

| | **Weight** | **T12** | **T5** | **LED** |
|---|---|---|---|---|
| **Efficacy** | 2 | 0 | + | + |
| **Lifetime** | 2 | 0 | 0 | + |
| **CRI** | 1 | 0 | + | + |
| **Cost** | 1 | 0 | - | - |
| **Environmental Waste** | 1 | 0 | 0 | + |
| **Total** | **-** | **0** | **+2** | **+4** |

This data was translated into a Pugh Chart, which was used to compare the various lights, while using the T12 option as a baseline (Table 4.2.2). If a lighting option performed better than the T12 baseline, it was assigned a "+". Options that performed worse than the fluorescent were assigned a "-". For any criterion, if one of the lighting options was within 10% of the baseline fluorescent value, it was considered equal, and received a "0". To outweigh the fluorescent option, lights must achieve higher efficacy, longer lifetime, higher CRI, lower cost, less environmental waste, or some combination of the above.

The weighting was based on the most important elements to our design, namely luminous efficacy and bulb lifetime. Having a high efficacy is important to obtain the most light possible (in lumens), while consuming the least power possible (in Watts). Since most fluorescent fixtures are turned on all day long to accommodate students, the bulb lifetime is also an important consideration. According to this weighting, the best performing option was LED lights, followed by T5 fluorescents. Differences between fluorescent, compact fluorescent, and incandescent lights were considered negligible. Thus, LED lights will be used as our final recommendation.

**4.3 Fixtures and Materials**

LED's are known to have a "long lifespan, high resistance to vibration and shock, low power consumption, high reliability and [they are] mercury free" (Chen and Chung, 2011). The main issues in retrofitting lighting fixtures with LED lamps are the major capital and labor costs involved with switching over the system. However, these issues can be easily overcome using a new product developed by major manufacturers such as Philips (Figure 2) and GE to minimize the complexity of the switch to a more efficient system. The LED tubes take the traditional fluorescent form and hook on the current fluorescent light fixture while the electric ballast is either "removed or bypassed". This technique utilizes an integrated AC/DC converter that converts the high-frequency AC power from the ballast into DC power for the LEDs.

Ballasts are the parts of a light fixture that hold and power the fluorescent light bulbs. Electronic ballasts are more efficient at providing energy-efficient power to the bulbs and have multiple advantages over older magnetic ballasts. Electronic ballasts can hold multiple bulbs and use less energy to power those bulbs. These work best with T8 bulbs for maximum energy saving. Part of their effectiveness is due to being better able to convert incoming electricity to the proper amount needed to power the bulbs, leading to less wasted energy. Switching from T12 to T5 may require the purchase of conversion kits depending on the strategy as they use different sockets and ballasts.


*Figure 4.3.1: Philips EnduraLED T8 light bulbs (Philips, 2014).*

By switching over to LEDs, it is possible to decrease power consumption and light pollution. According to Chen and Chung (2011), the overall efficacy of the retrofit LED was found to be 50 lumens/Watt as compared to the fluorescent system, which obtained an efficacy of 60.6 lumens/Watt. Even though the system was not as efficient, it is a developing technology and can be improved upon by either "reducing the power consumption of the DC circuit" or by "increasing the efficacy of the LED". The LED system does, however, have much less of a negative environmental impact due to the absence of mercury in the lamps. By using this retrofit method, the environmental waste would be minimal since the existing light fixtures would be maintained.

**4.4 General Details**

During a meeting with David Balcombe in January 2014, our team was asked to investigate the potential return on investment for lighting replacement projects at RVC. The following section describes the estimated cost of replacement for T12 fluorescent fixtures and Incandescent bulbs, the estimated reduction in electrical energy consumption, and the simple pay-back period.

In this analysis, all known T12 and Incandescent light fixtures at RVC will be considered for replacement. The potential replacement fixtures will include LED and T5 fluorescent technologies. Occupancy sensor considerations were excluded per expressed concern over building and fire code compliance.  Per request of Mr. Balcombe, replacement of existing fluorescent T8 fixtures was excluded from consideration.

Based on the RVC Lighting Inventory performed by MEP, our team identified the following T12 fluorescent and Incandescent fixtures for replacement:

Table 4.4.1: Existing Lighting in RVC considered for replacement (CFL & T8 excluded)

| Lamp Type | Length (ft.) | Unit Wattage (W) | Number of Fixtures | Total Number of Lamps | Total Wattage (kW) | Estimated Annual Consumption (kWh) |
|---|---|---|---|---|---|---|
| T12 single | 3 | 30 | 8 | 8 | 0.2 | 2,102.4 |
| T12 single | 4 | 40 | 175 | 175 | 7.0 | 61,320.0 |
| T12 double | 4 | 80 | 76 | 152 | 6.1 | 53,260.8 |
| Incandescent | bulb | 60 | 57 | 57 | 3.4 | 29,959.2 |
| **TOTALS** | **-** | **-** | **316** | **392** | **16.7** | **146,642.4** |

In order to determine the estimated annual cost savings and return on investment, we must first estimate the current cost of operation for the lighting considered above. Annual cost of operation of current lighting in RVC (to be replaced) was estimated through the following equation:

Equation 4.4.1: Estimation of Annual cost of operation

$$\text{Annual Cost} = \text{Annual Demand Cost} + \text{Annual Consumption Cost}$$
$$\text{where:}$$
$$\text{Annual Demand Cost} = \text{Total Rated Wattage (kW)} * 95\% * 12\,\frac{\text{bills}}{\text{year}} * 12.18\left(\frac{\$}{\text{kW}}\right)$$
$$\text{Annual Consumption Cost} = \text{Total Rated Wattage (kW)} * 8760\,\frac{\text{hours}}{\text{year}} * 0.0304\,(\frac{\$}{\text{kWh}})$$

The calculations were performed by accounting for rated wattage, assuming continuous operation (8,760 hours per year) and using McGill's current demand cost of $12.18 per kW (95% of monthly peak demand) and consumption cost of $0.0304 per kWh.

Table 4.4.2: Estimated operating cost for current lighting in RVC considered for replacement

| **Lamp Type** | **Annual Demand Cost** | **Annual Consumption Cost** | **Annual Cost** |
|---|---|---|---|
| T12 single | $33.32 | $63.91 | $97.24 |
| T12 single | $971.96 | $1,864.13 | $2,836.09 |
| T12 double | $844.22 | $1,619.13 | $2,463.35 |
| Incandescent | $474.87 | $910.76 | $1,385.63 |
| **TOTALS** | **$2,324.38** | **$4,457.93** | **$6,782.31** |

**4.5: Lighting Project 1 – T5 & CFL**

For the following project proposal, a rough cost estimate was used to determine the installation cost of replacing all T12 fluorescent fixtures and incandescent light bulbs with T5 fluorescent fixtures and CFL light bulbs. Actual installation costs may vary widely from costs reported here based on a variety of factors including price of specific fixture selected and any potential energy efficiency rebates obtained from Hydro Quebec and/or the Ministry of Natural Resources. For all cases, our team used judgment to select appropriate fixtures and light bulbs that fell in the mid-range of available pricing.

For replacement calculations, our team selected the following fixtures:

Table 4.5.1: Replacement T5 fixtures for RVC

| Lamp Type | Model | Supplier | Dimensions | No. of Lamps | Unit Wattage (W) | Fixture Price | Lamp Price | Unit Total Cost |
|---|---|---|---|---|---|---|---|---|
| T5 double | Lithonia SP5 | Grainger Industrial Supply | 24"x48" | 2 | 56 | $224.50 | $5.99 | $236.48 |
| T5 single | Canlyte SV Strip T5 (4 ft.) | Westburne Electrical Supply | 2"x46" | 1 | 28 | $60.53 | $5.99 | $66.52 |
| T5 single | Canlyte SV Strip T5 (3 ft.) | Westburne Electrical Supply | 2"x34" | 1 | 21 | $60.53 | $5.99 | $66.52 |
| CFL | N/A | Westburne Electrical Supply | 4" | 1 | 13 | $0.00 | $2.99 | $2.99 |

The total material cost was determined by summing the unit total cost for each fixture being replaced.

Table 4.5.2 Material Cost for T5 & CFL Replacement

| Lamp Type | Total Unit Cost | Number of Fixtures | Total Cost |
|---|---|---|---|
| T5 double | $236.48 | 76 | $17,972.48 |
| T5 single 4' | $66.52 | 175 | $11,641.00 |
| T5 single 3' | $66.52 | 8 | $532.16 |
| CFL | $2.99 | 51 | $152.49 |
| **Total Material Cost** | - | - | **$30,298.13** |

For labor costs, it is assumed that each fixture will take an average of 30 minutes to replace and that each CFL bulb will take an average of 5 minutes to replace. A labor rate of $100 per hour is used, assuming that the job will be completed by 2 people.

Table 4.5.3. Installation Cost for T5 & CFL Replacement:

| Lamp Type | Installation Unit Cost | Number of Fixtures | Total Cost |
|---|---|---|---|
| T5 double | $50.00 | 76 | $3,800.00 |
| T5 single 4' | $50.00 | 175 | $8,750.00 |
| T5 single 3' | $50.00 | 8 | $400.00 |
| CFL | $8.33 | 51 | $424.83 |
| **Total Installation Cost** | - | - | **$13,374.83** |

The last step in the cost estimate is to factor in an allowance for unforeseen circumstances which may increase the overall price of installation quoted by a contractor. Generally, 10% is a sufficient allowance for revisions. In this case, the revision allowance will factor in potential price increases a contractor might apply; for example, cost of disposal of the existing fixtures and labor and materials for minor touch-ups or modifications after installation.

Table 4.5.4. Estimated Cost for T5 & CFL Replacement:

| T5 & CFL Replacement | Material Cost | Installation Cost | Total Cost |
|---|---|---|---|
| T5 double | $17,972.48 | $3,800.00 | $21,772.48 |
| T5 single 4' | $11,641.00 | $8,750.00 | $20,391.00 |
| T5 single 3' | $532.16 | $400.00 | $932.16 |
| CFL | $152.49 | $424.83 | $577.32 |
| **Sub-Total** | **$30,298.13** | **$13,374.83** | **$43,672.96** |
| 10% Revision | - | - | $4,367.30 |
| **TOTAL ESTIMATE** | - | - | **$48,040.26** |

To estimate the consumption, and therefore, the annual cost of the proposed T5 and CFL lighting project, we use the method shown previously:

Table 4.5.5. Estimated Annual Consumption for T5 & CFL Replacement

| Lamp Type | Unit Wattage (W) | Number of Fixtures | Total Wattage (kW) | Estimated Annual Consumption (kWh) |
|---|---|---|---|---|
| T5 double | 56 | 76 | 4.3 | 37,282.6 |
| T5 single 4' | 28 | 175 | 4.9 | 42,924.0 |
| T5 single 3' | 21 | 8 | 0.2 | 1,471.7 |
| CFL | 13 | 51 | 0.7 | 5,807.9 |
| **TOTALS** | **-** | **310** | **10.0** | **87,486.1** |

Table 4.5.6: Estimated Operating Cost for T5 & CFL Replacement

| Lamp Type | Annual Demand Cost | Annual Consumption Cost | Annual Cost |
|---|---|---|---|
| T5 double | $590.95 | $1,133.39 | $1,724.34 |
| T5 single 4' | $680.37 | $1,304.89 | $1,985.26 |
| T5 single 3' | $23.33 | $44.74 | $68.07 |
| CFL | $92.06 | $176.56 | $268.62 |
| **TOTALS** | **$1,386.71** | **$2,659.58** | **$4,046.29** |

Lighting Project 1 provides an estimated annual operating cost of $4,046.29 whereas the current T12 fluorescent and incandescent bulbs cost an estimated $6,782.13 per year. Therefore, Light Project 1 provides an estimated savings of $2,736.02 per year.

Equation 4.5.1: The return on investment (ROI) or simple payback period calculation

$$\mathrm{ROI} = \frac{\text{Total Estimated Cost}}{\text{Estimated Annual Savings}}$$

$$\mathrm{ROI} = \frac{\$48{,}040.26}{\$2{,}735.84} = 17.56 \text{ years}$$

The ROI found for Lighting Project 1 is less than optimal. It varies for specific organizations; however, many companies will impose a minimum ROI of 10 years for projects to be considered economically viable. If this approach is taken, than the maximum viable cost for Project 1 would be $27,358.40. The ROI of Project 1 may be improved by several methods including: applying for and obtaining energy efficiency rebates from Hydro Quebec of the Ministry of Natural Resources or selecting less expensive lighting fixtures than those presented here.

**4.6 Lighting Project 2 – LED Replacement**

It should be noted that although a wide variety of (less expensive) retrofit kits exist for T12 to T5 or T12 to LED conversion, due to the age of the existing fixtures our team focused on a complete replacement of the fixture in order to obtain the best manufacturer-intended results. Many older T12 fixtures currently installed in RVC feature magnetic ballasts whereas newer T5 fixtures utilize electronic ballasts; as a result the ballasts would also need to be changed (unless self-ballasted retrofit kits were selected). Additionally, utilizing a fixture with a troffer and diffuser specifically designed for that lamp size generally produces more efficient light output than retrofits. In short, retrofits options may provide for a more economical alternative to complete fixture replacement; however, they should be pursued with caution. If there is interest in pursuing a retrofit option, our team recommends performing a selective trial run with a few fixtures in order to evaluate operation, reliability and occupant feedback.

For the following project proposal, a rough cost estimate was used to determine the installation cost of replacing all T12 fluorescent fixtures and incandescent light bulbs with LED fixtures and LED replacement bulbs designed to fit standard incandescent/CFL fixtures. For all cases, our team used judgment to select appropriate fixtures and light bulbs that fell in the mid-range of available pricing.

For replacement calculations, our team selected the following fixtures:

Table 4.6.1: Replacement LED Fixtures for RVC

| Lamp Type | Model | Supplier | Dimensions | Total Wattage (W) | Fixture Price | Lamp Price | Unit Total Cost |
|---|---|---|---|---|---|---|---|
| LED 2x4' | Lithonia 2GTL | Westburne Electrical Supply | 24"x48" | 40.0 | $182.15 | $0.00 | $182.15 |
| LED 1x4' | Lithonia MNSL-MV-M6 | Westburne Electrical Supply | 2"x48" | 20.0 | $142.63 | $0.00 | $142.63 |
| LED 1x3' | Nora LED Bravo Linear | BEES Lighting | 2"x36" | 10.8 | $169.11 | $0.00 | $169.11 |
| LED bulb | Verbatim LED bulb | BEES Lighting | 4" | 10.0 | $0.00 | $19.98 | $19.98 |

The total material cost was determined by summing the unit total cost for each fixture being replaced.

Table 4.6.2. Material Cost for LED Replacement

| Lamp Type | Unit Total Cost | Number of Fixtures | Total Cost |
|---|---|---|---|
| LED 2x4' | $182.15 | 76 | $13,843.40 |
| LED 1x4' | $142.63 | 175 | $24,960.25 |
| LED 1x3' | $169.11 | 8 | $1,352.88 |
| LED bulb | $19.98 | 51 | $1,018.98 |
| **Total Material Cost** | - | - | **$41,175.51** |

For labor costs, it is assumed that each fixture will take an average of 30 minutes to replace and that each LED bulb will take an average of 5 minutes to replace. A labor rate of $100 per hour is used, assuming that the job will be completed by 2 people.

Table 4.6.3: Labor Cost for LED Replacement

| Lamp Type | Installation Unit Cost | Number of Fixtures | Total Cost |
|---|---|---|---|
| LED 2x4' | $50.00 | 76 | $3,800.00 |
| LED 1x4' | $50.00 | 175 | $8,750.00 |
| LED 1x3' | $50.00 | 8 | $400.00 |
| LED bulb | $8.33 | 51 | $424.83 |
| **Total Installation Cost** | - | - | **$13,374.83** |

The last step in the cost estimate is to factor in an allowance for unforeseen circumstances which may increase the overall price of installation quoted by a contractor. Generally, 10% is a sufficient allowance for revisions. In this case, the revision allowance will factor in potential price increases a contractor might apply; for example, cost of disposal of the existing fixtures and labor and materials for minor touch-ups or modifications after installation.

Table 4.6.4 Estimated Cost for LED Replacement

| Lamp Type | Material Cost | Installation Cost | Total Cost |
|---|---|---|---|
| LED 2x4' | $13,843.40 | $3,800.00 | $17,643.40 |
| LED 1x4' | $24,960.25 | $8,750.00 | $33,710.25 |
| LED 1x3' | $1,352.88 | $400.00 | $1,752.88 |
| LED bulb | $1,018.98 | $424.83 | $1,443.81 |
| **Sub-Total** | **$41,175.51** | **$13,374.83** | **$54,550.34** |
| 10% Revision | - | - | $5,455.03 |
| **TOTAL ESTIMATE** | **-** | **-** | **$60,005.37** |

To estimate the consumption, and therefore, the annual cost of the proposed T5 and CFL lighting project, we use the method shown previously:

Table 4.6.5. Estimated Annual Consumption for LED Replacement Project

| Lamp Type | Unit Wattage (W) | Number of Fixtures | Total Wattage (kW) | Estimated Annual Consumption (kWh) |
|---|---|---|---|---|
| LED 2x4' | 40.0 | 76 | 3.0 | 26,630.4 |
| LED 1x4' | 20.0 | 175 | 3.5 | 30,660.0 |
| LED 1x3' | 10.8 | 8 | 0.1 | 756.9 |
| LED bulb | 10.0 | 51 | 0.5 | 4,467.6 |
| **TOTALS** | **-** | **310** | **7.1** | **62,514.9** |

Table 4.6.6: Estimated Annual Operation Cost for LED Replacement Project

| Lamp Type | Annual Demand Cost | Annual Consumption Cost | Annual Cost |
|---|---|---|---|
| LED 2x4' | $422.11 | $809.56 | $1,231.67 |
| LED 1x4' | $485.98 | $932.06 | $1,418.05 |
| LED 1x3' | $12.00 | $23.01 | $35.01 |
| LED bulb | $70.81 | $135.82 | $206.63 |
| **TOTALS** | **$990.90** | **$1,900.45** | **$2,891.36** |

Lighting Project 2 provides an estimated annual operating cost of $2,891.36 whereas the current T12 fluorescent and incandescent bulbs cost an estimated $6,782.13 per year. Therefore, Light Project 2 provides an estimated savings of $3,890.77 per year.

Equation 4.6.1: The return on investment (ROI) or simple payback period calculation

$$\mathrm{ROI} = \frac{\text{Total Estimated Cost}}{\text{Estimated Annual Savings}}$$

$$\mathrm{ROI} = \frac{\$60{,}005.37}{\$3{,}890.77} = 15.42 \text{ years}$$

Again, the ROI found for Lighting Project 2 is less than optimal to be considered economically viable on energy-savings alone. If a minimum ROI of 10 years is selected, then the maximum viable cost for Project 2 would be $38,907.70.

**4.7 Lighting Project – Conclusion**

For comparison, presented below is a table with related cost and energy savings for each project:

Table 4.7.1: Summary of Lighting Projects

| | **Current** | **Project 1** | **Project 2** |
|---|---|---|---|
| Lamp Type | T12 & Fluorescent | T5 & CFL | LED & LED bulb |
| Total Demand (kW) | 16.7 | 10.0 | 7.1 |
| Annual Consumption (kWh) | 146,642.4 | 87,486.1 | 62,514.9 |
| Demand Cost | $2,324.38 | $1,386.71 | $990.90 |
| Consumption Cost | $4,457.93 | $2,659.58 | $1,900.45 |
| Cost-Savings | - | $2,736.02 | $3,890.96 |
| Installation Cost | - | $48,040.26 | $60,005.37 |
| Return on Investment (years) | - | 17.6 | 15.4 |

Both projects provide significantly lower consumption and demand estimates. Implementing Project 1 would reduce both lighting demand and annual consumption by nearly 40%. Implementing Project 2 would reduce both lighting demand and annual consumption by nearly 57%.

Our team believes that Lighting Option 2 (LED) is superior to Lighting Option 1 (CFL & T5). Despite being the more expensive of the two projects, Lighting Option 2 has a slightly lower return on investment due to being the more efficient alternative. Additionally, when factoring results from the Pugh chart analysis shown previously (Table 4.1.1), we feel that the improved efficiency, lifespan and decreased environmental impact of LED outweighs the price increase over fluorescent technologies.

## 5. Scotiabank EcoLiving Awards

As per the requirements of the Design 3 course, the project was to be entered in an engineering competition that was considered fitting for the chosen topic. As this project dealt with energy efficiency in a residency environment, the team decided to apply for the Scotiabank EcoLiving Award. This competition is fittingly targeted towards innovative products or services in the residential sector and is aiming towards creating a greener, more energy efficient manner of living. For this award, the facilitation of major reductions in energy usage along with innovation and potential for applications are the judging criteria's.

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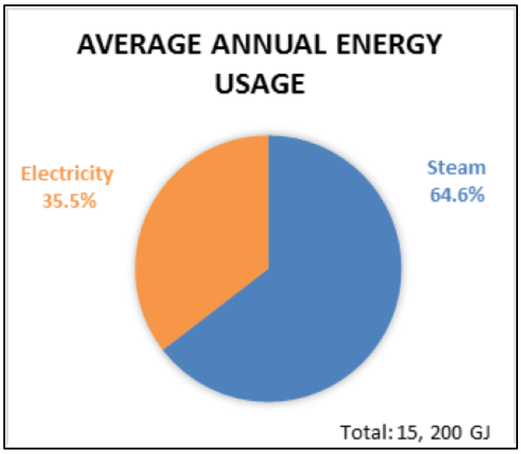
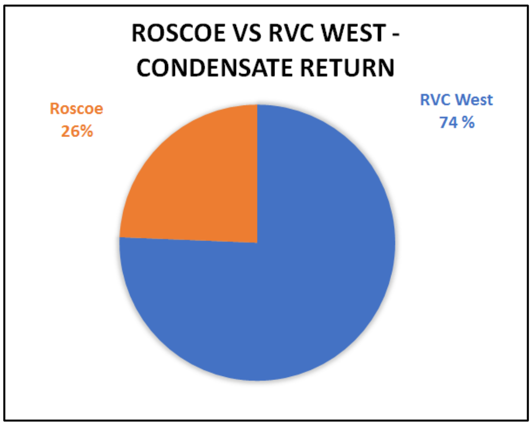
## Appendices

### Appendix A: Tables and Graphs

Appendix A.1: Average Annual Energy usage




Appendix A.2: Steam Usage in RVC




Appendix A.3: Model Parameters

| | Loops | Initial Temperature (°C) | Initial Pressure (kPa) | Final Pressure (kPa) | Pipe thickness (m) | Insulation thickness (cm) |
|---|---|---|---|---|---|---|
| **Current** | **Current network** | 60 | 448.16 | 372.91 | 0.005 | 0.025 |
| **Option 1** | **Cafeteria / Middle Music** | 60 | 448.16 | 417.49 | 0.005 | 0.025 |
| | **East Music** | | | 429.13 | | |
| **Option 2** | **Cafeteria** | 60 | 448.16 | 427.47 | 0.005 | 0.025 |
| | **Middle Music** | | | 397.10 | | |
| | **East Music** | | | 429.13 | | |

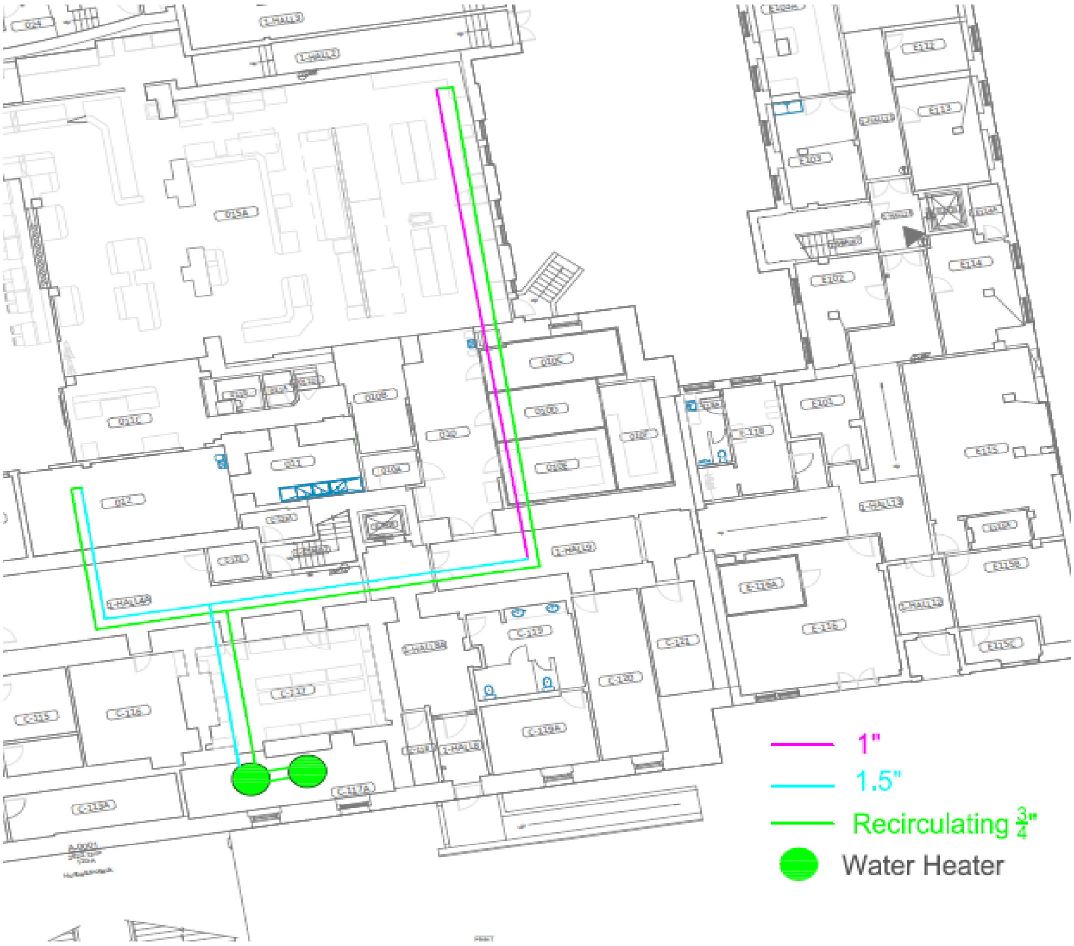
## Appendix A.4: Option 1 cost breakdown

| Option 1 cost breakdown | | | |
|---|---|---|---|
| **Cafeteria loop**<br>**Item** | **Price ($/unit)** | **#** | **Price ($)** |
| Hot water heaters for east music | 4000 | 2 | 8000 |
| Circulating pumps for east music | 800 | 1 | 800 |
| 90 elbows 1.5'' | 65 | 3 | 195 |
| 90 elbow 3/4'' | 80 | 4 | 320 |
| Tees 3/4'' | 107 | 1 | 107 |
| Tees 1.5'' | 122 | 1 | 122 |
| 1.5'' copper pipe (6 ft) | 113 | 18 | 2034 |
| 3/4'' copper pipe (6ft) | 55 | 18 | 990 |
| Cost of extra insulation (3ft) | 35 | 72 | 2520 |
| Aebstos removal (4'' leftover) | 25 | 0 | 0 |
| Cost of labor | | 1 | 15000 |
| Subtotal cost | | | 30088 |
| **Middle Music** | | | |
| Hot water heaters for east music | 2000 | 1 | 2000 |
| Circulating pumps for east music | 800 | 1 | 800 |
| 90 elbows 1.5'' | 80 | 2 | 160 |
| 90 elbow 3/4'' | 80 | 3 | 240 |
| Tees 3/4'' | 107 | 1 | 107 |
| Tees 1.5'' | 107 | 2 | 214 |
| 2'' copper pipe (5 ft) | 119 | 2 | 238 |
| 1.5'' copper pipe (6 ft) | 113 | 5 | 565 |
| 1'' copper pipe (6ft) | 80 | 0 | 0 |
| 3/4'' copper pipe (6ft) | 55 | 5 | 275 |
| Globe valve | 80 | 1 | 80 |
| Cost of extra insulation (3ft) | 35 | 23 | 805 |
| Aebstos removal (4'' leftover) | 25 | 0 | 0 |
| Cost of labor | | 1 | 15000 |
| Subtotal cost | | | 20484 |
| **East Music** | | | |
| Hot water heaters for east music | 2000 | 1 | 2000 |
| Circulating pumps for east music | 800 | 1 | 800 |
| 90 elbows 4'' | 150 | 5 | 750 |
| 90 elbow 3/4'' | 80 | 5 | 400 |
| Tees 3/4'' | 107 | 2 | 214 |
| 2'' copper pipe (5 ft) | 119 | 1 | 119 |
| 1.5'' copper pipe (6 ft) | 113 | 1 | 113 |
| 1'' copper pipe (6ft) | 80 | 2 | 160 |
| 3/4'' copper pipe (6ft) | 55 | 2 | 110 |
| Globe valve | 80 | 1 | 80 |
| Cost of extra insulation (3ft) | 35 | 12 | 420 |
| Aebstos removal (4'' leftover) | 25 | 383 | 9575 |
| Cost of labour | | 1 | 15000 |
| Subtotal cost | | | 29741 |
| Total cost of investment | | | 80313 |

## Appendix B: Pipe Schematics

Appendix B.1: Option 1 - All loops are represented according to pipe diameters

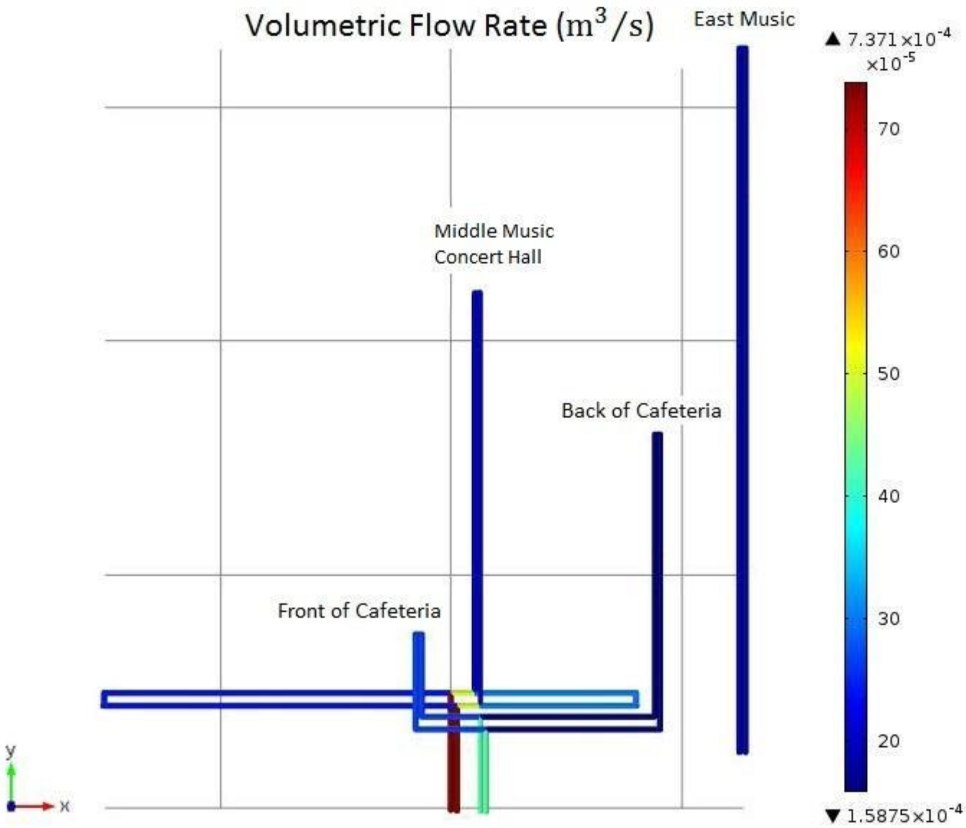
Appendix B.2: Option 1 - Cafeteria loop according to pipe diameters



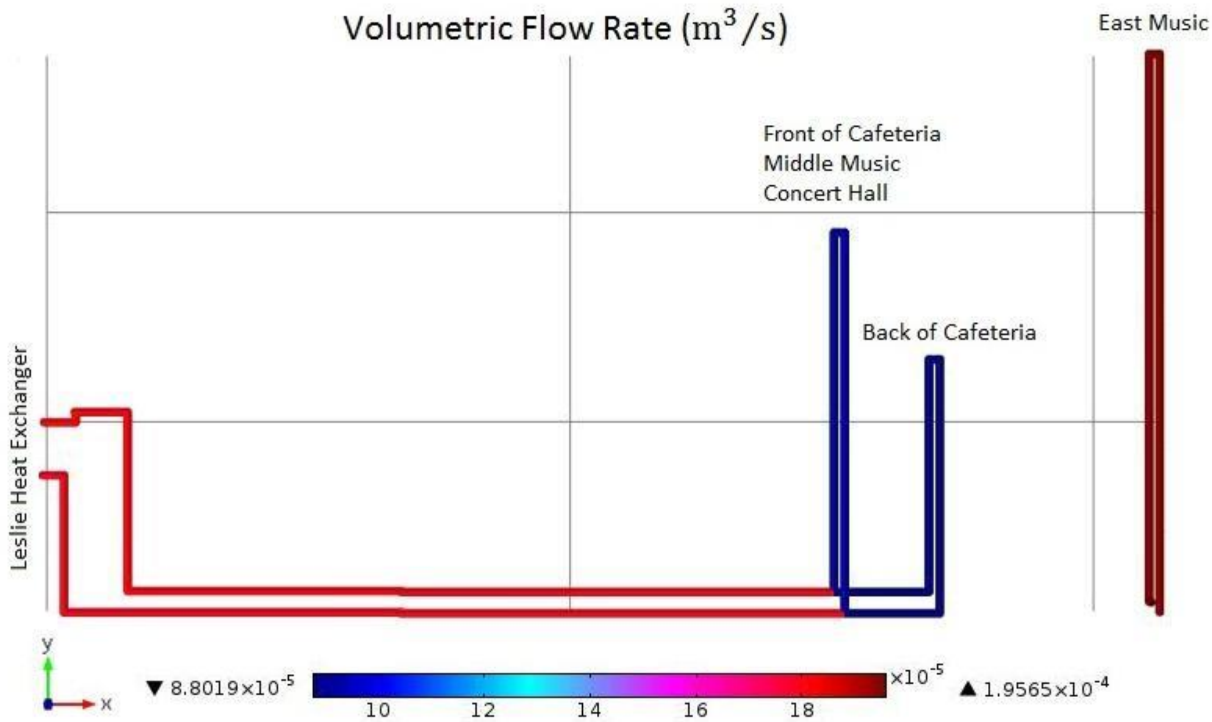
Appendix B.3: Option 1 - Middle Music, RVC and East Music loops according to pipe diameters

**Appendix C: Simulation Figures**

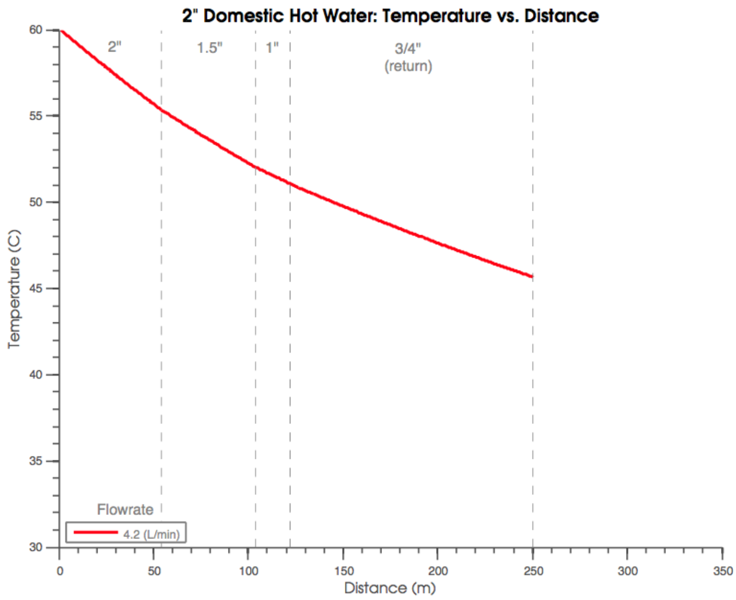
Appendix C.1: Hot domestic water - Volumetric flow rate option 1

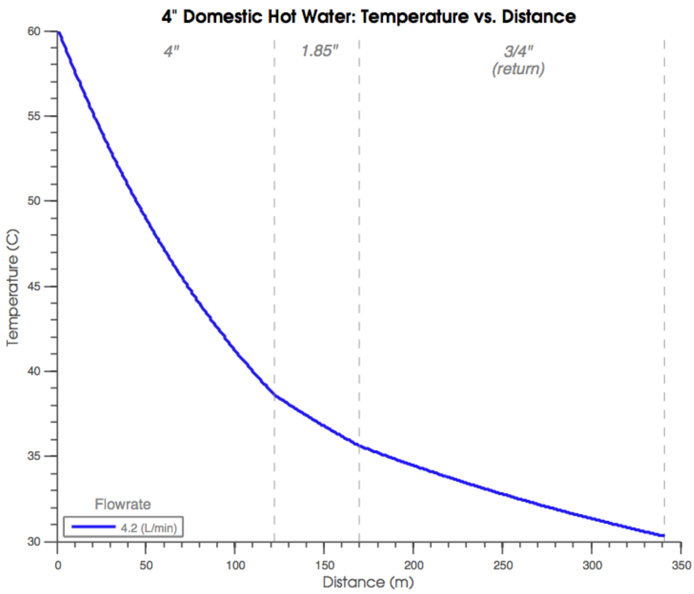



Appendix C.2: Hot domestic water - Volumetric flow rate option 2



Appendix C.3: Matlab Simulation showing Temperature vs Distance of the 2” and 4” Pipes




The pipe is discretized spatially in terms of length, where flow rate and diameter are used to calculate time for water to flow between each unit of discretization. Discretized units are assumed to be of uniform temperature, and rate of heat loss to ambient external air is calculated for each unit. The product of rate of heat loss and time produces energy loss, which is then converted to temperature loss using the mass of water in a given unit of discretization. A recurrence relation is used to determine heat loss iteratively across a given length of pipe. As initial temperature decreases over the length of pipe, heat loss also decreases resulting in an exponential decay of heat transfer approaching ambient air temperature. The simulation takes into account:

- Conduction through copper piping
- Conduction through asbestos insulation
- Natural convection