A Single Family Residence in Edmonton: Heating System Design Report

MecE 466: Building Systems Design

November 29th, 2019

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November 29, 2019

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Dear Dr. Zhong,

On behalf of Design Team Number 4, it is my pleasure to present our design for the 2-story, single-family residence in Edmonton, Alberta as you have outlined. The attached report fully outlines the heating loads, economic analysis, furnace and humidifier equipment selection, duct design, and recommendations. These are all in compliance with the Alberta building code and ASHRAE standards. Assumptions were made when necessary and were made to be conservative and in compliance to the Codes and Standards.

Should you have any questions, feel free to contact me with any further inquiries. I can be reached by phone at (587) 937-7811 or by e-mail at hajisali@ualberta.ca

Thank you for your consideration.

Sincerely,

Sepehr Haji-Salimi

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1 INTRODUCTION

A new, 2176 sq. ft, two-floor residential house (single detached residence) is to be built in Edmonton, Alberta. This residential building is to be built according to local, provincial and Federal building code guidelines. Floor plans of the aforementioned building to be used in the design phase are shown in the figures below. Although exact building materials were not provided due to conflicts with non-disclosure agreements, building materials typically used in the construction of residential buildings in the area were selected. This report was aimed at showing all heat load calculations, design, analysis and recommendations for the HVAC system, as well as simplified indoor environmental quality evaluation. The sizing and selection done covers only the heating and humidifying equipment, this limitation also applies to the listed equipment specifications and cost estimates. The performance of natural gas air furnace system was compared to the combined performance of natural gas air furnace coupled with an air source heat pump (ASHP) and a recommendation was made based on the more economic system. Afterwards, a humidifier and, based on the results of the economic system analysis, a furnace was selected to meet the requirements of the buildings design conditions and loads.

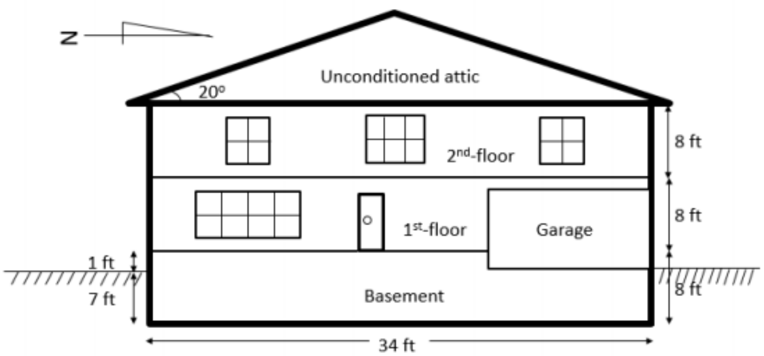


Figure 1: Side View of Building Floor Layout with Dimensions

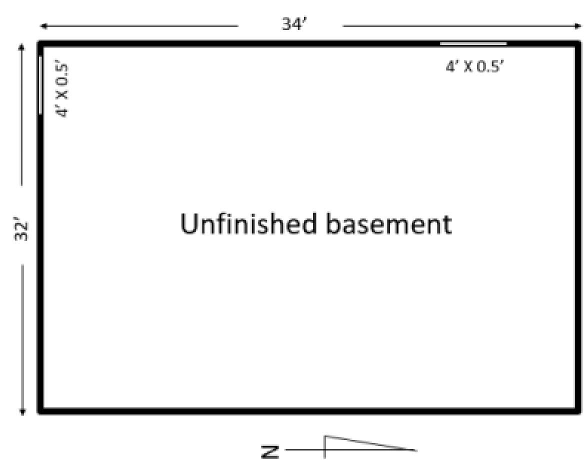


Figure 2: Top View of Basement Floor Layout with Dimensions

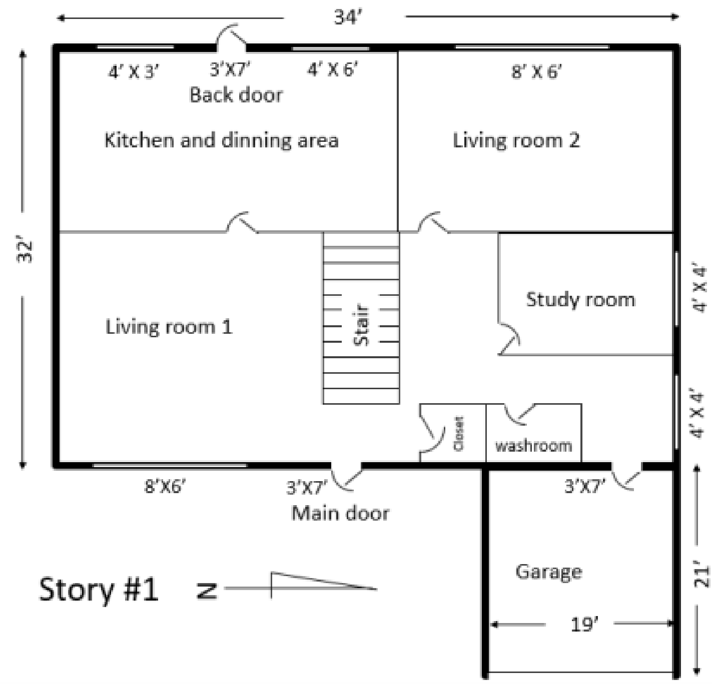


Figure 3: Top View of First Floor Layout with Dimensions

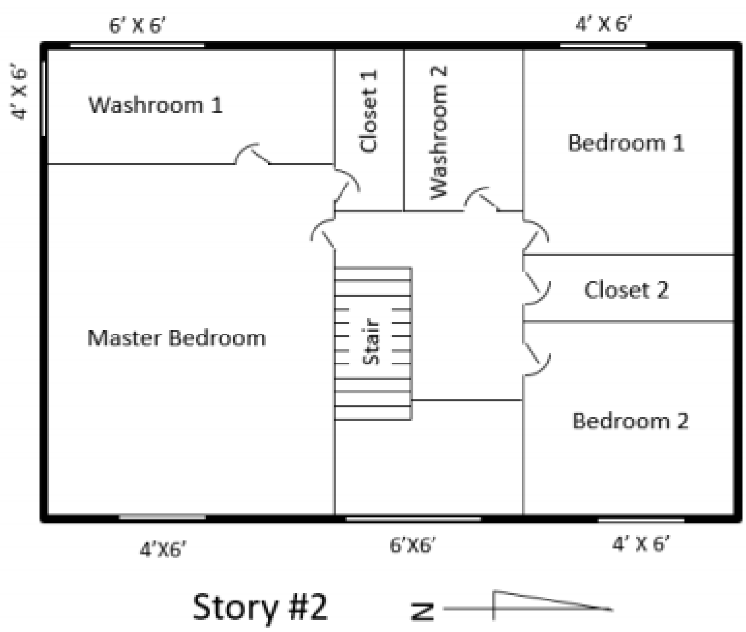


Figure 4: Top View of Second Floor Layouts with Dimensions

2 ASSUMPTIONS, CONSTRAINTS, & CODE COMPLIANCE

To ensure the designed heating system was suitable for this building, the designers made various assumptions regarding the house construction and system construction/performance. These assumptions were made with the help of various standards as well as Howell et al. [1]. These assumptions were used to develop a heating and humidifying system that is suitable for the chosen location of Edmonton, Alberta. Due to the presence of a Non-Disclosure Agreement (NDA) protecting the exact makeup of building assemblies, various construction assumptions were made to comply with the minimum requirements of applicable standards listed in section 2.1. Using minimum compliance provides the design with an ensured factor of safety, as the actual building construction must meet or exceed the conditions used to complete the detailed design of this heating system.

The final list of important design decisions and data is included below in Table 1.

Table 1: Indoor and Outdoor Design Conditions

Design Item:	**Value:**	**Note:**
Location	Edmonton City Centre AWOS, AB, Canada	Design Location
Latitude	53.570 N	a
Longitude	113.520 W	a
Elevation [m]	671	a
Outdoor Design Temperature [°F]	-14.4	a
Outdoor Humidity Ratio [lb_w/lb_a]	0.0002	a
Indoor Temperature [°F]	70	b, d
Indoor Relative Humidity [%]	30	b, d
Indoor Humidity Ratio [lb_w/lb_a]	0.005	c
Indoor Air Velocity [fpm]	20	d
Average Winter Temperature, t_m [°F]	13.28	e
Ground Temperature, t_{gr} [°F]	-8.72	f
Ground Surface Amplitude, A [°F]	22	$t_{gr} = t_m - A$

Notes

a. From 'Design Conditions for Edmonton-ASHRAE 2017'
b. Indoor air conditions to satisfy ASHRAE 55 [2]
c. Psychometric Chart
d. See Section 2.1.1 and [6]
e. January average temperature using row 6 from 'Design Conditions for Edmonton-ASHRAE-2017'
f. From Ground surface temperature from Figure 6-1 in [1]

2.1 Compliance to Codes and Standards

The assumptions given in section 2.2 were made with reference to the following codes and standards:

i. ASHRAE 55-2017 – *Thermal Environmental Conditions for Human Occupancy* [2]
ii. ASHRAE 62.2-2016 – *Ventilation and Acceptable Indoor Air Quality in Residential Buildings* [3]
iii. ASHRAE 90.2-2018 – *Energy-Efficient Design of Low-Rise Residential Buildings* [4]
iv. Alberta Building Code 2016 – *Section 9.36, Prescriptive Energy Efficiency Requirements for Houses* [5]

These standards provided the designers with information necessary to develop the heating system for the given project, despite not knowing all details of the house construction.

2.1.1 ASHRAE Standard 55-2017

This standard was used to determine the appropriate Indoor Design Conditions for occupancy of this single-family home. As shown in Figure 5, the graphical method for this standard was used to determine the appropriate indoor temperature and humidity. The Centre for the Built Environment (CBE) Thermal Comfort Tool [6] was used to specify indoor conditions that comply with this standard.

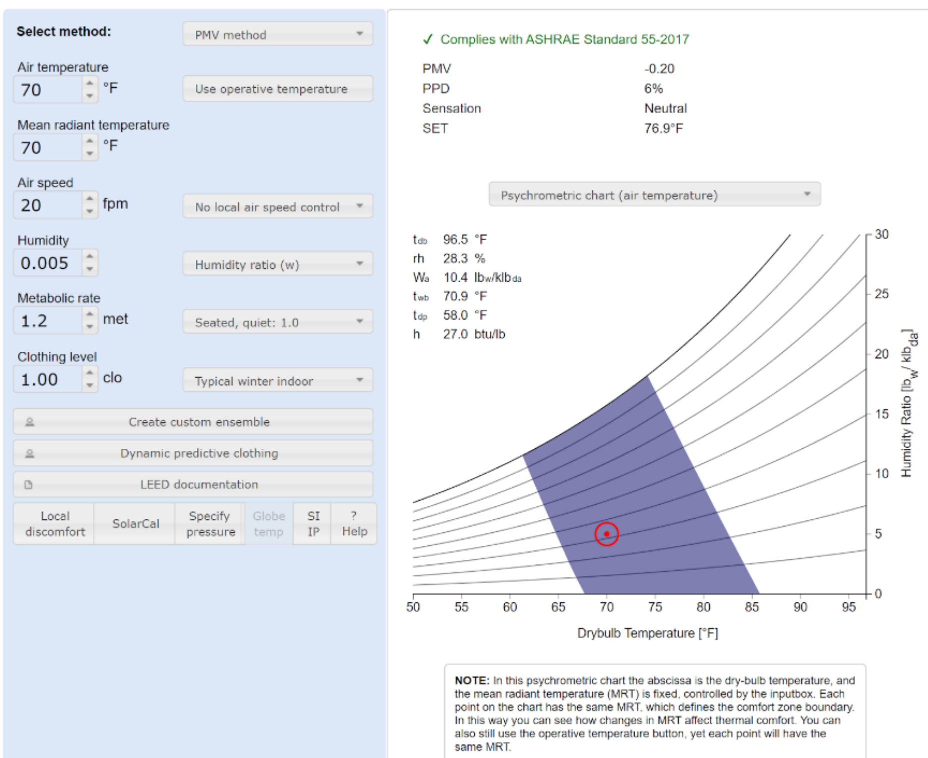


Figure 5: Graphical determination of indoor air conditions based on ASHRAE Standard 55 (taken from [6])

2.1.2 ASHRAE Standard 62.2-2016

This standard governed decisions regarding airflow through the house, allowing the calculation of required ventilation from mechanical fan systems. This standard also provides limits to building infiltration which impacted the house construction requirements (see 2.2.76).

2.1.3 ASHRAE Standard 90.2-2018

This standard is concerned with the construction of energy-efficient low-rise buildings. The tables within ASHRAE 90.2 provide allowable U-values and R-values for construction assemblies as well as standards regarding the operation and efficiency of heating equipment such as Furnaces and Heat Pumps.

2.1.4 Alberta Building Code 9.36

The Alberta Building Code was used to determine the appropriate construction assemblies for this house located in Edmonton. The assemblies indicated in section 2.2.6 were chosen to comply with the minimum R-Values dictated in the Building Code to ensure the designed heating system will properly function for a standard house built in this part of Alberta.

2.2 Assumptions and Constraints

2.2.1 Scope of Mechanical Design

The following inclusions and exclusions dictate what parts of the building will be included in this project, impacting the heating load, ductwork, and equipment determination.

i. **Inclusions**
The spaces included in the heating design for this house are the basement, main floor, and second floor. These are all considered to be one zone controlled by a single thermostat and humidistat (See Appendix D for the design and placement of ductwork/control systems). The exterior of these spaces are considered to be against outdoor air, an unconditioned garage, or below grade.

ii. **Exclusions**
The designed heating system only covers the occupied areas of the house, this scope excludes the attic and the garage from conditioning. These spaces are considered *buffer spaces* that will impact transmission and infiltration losses of the conditioned areas, but any losses from these spaces will not be included in the heating load analysis of the building. The only exception to this is losses from the ductwork that is housed in the attic.

2.2.2 ASHRAE Standard 55-2017

i. As this home is assumed to use a forced-air furnace (or a furnace/heat pump combination), it was assumed that the operating temperature (t_o) is equal to the indoor air temperature (t_a), implying that the Mean Radiant Temperature (MRT) is also equal to t_a.

ii. To determine the appropriate comfort range, the occupants of this house were assumed to be wearing light winter clothing (jeans, shirt, etc) that equates to 1.0 clo of clothing insulation (Figure 5).

iii. It was assumed the occupants of the house are performing at most light work such as cooking. This led to the metabolic rate assumption of 1.2 met (Figure 5).

iv. As a conservative assumption regarding humidification requirements, the outdoor humidity ratio (W_o) is assumed to be 0 (no moisture).

2.2.3 ASHRAE Standard 62.2-2016

i. Procedures from this standard will be completed using data for a 3-Bedroom, single family detached residence.

ii. Section 4.1.2.f of this standard dictates that the infiltration rate cannot exceed two-thirds of the total required ventilation rate determined using the method in that section. See Section 2.2.7 and Appendix A-3 for the detailed implementation of this standard.

iii. To meet air quality requirements in this standard, all supply air is assumed to be 100% Outdoor Air, there is no recirculation.

iv. Any determined ventilation rates must meet or exceed the total ventilation determined with this Standard, with local ventilation achieving 20 cfm in continuously occupied rooms (bedrooms, main living room).

2.2.4 ASHRAE 90.2-2018

i. To simplify the heat losses and create conservative results, all windows were assumed to be operable. Any fenestration selections were made to comply to ASHRAE 90.2 and the Alberta Building Code.

2.2.5 Alberta Building Code 2016, Section 9.36

i. Figure 6 below provides the minimum R-Value requirements for various building assemblies in the three climate zones that exist in Alberta. As Edmonton is located in Zone 7A, R-Value requirements (I-P values given in parentheses) are taken from the center column.

	Zone 6		Zone 7A		Zone 7B	
	No HRV RSI (R)	HRV RSI (R)	No HRV RSI (R)	HRV RSI (R)	No HRV RSI (R)	HRV RSI (R)
Ceiling below attics	8.67 (49.2)	8.67 (49.2)	10.43 (59.2)	8.67 (49.2)	10.43 (59.2)	10.43 (59.2)
Cathedral ceilings and flat roofs	4.67 (26.5)	4.67 (26.5)	5.02 (28.5)	5.02 (28.5)	5.02 (28.5)	5.02 (28.5)
Above grade walls	3.08 (17.5)	2.97 (16.9)	3.08 (17.5)	2.97 (16.9)	3.85 (21.9)	3.08 (17.5)
Floors over unheated spaces	4.67 (26.5)	4.67 (26.5)	5.02 (28.5)	5.02 (28.5)	5.02 (28.5)	5.02 (28.5)
Rim joists	3.08 (17.5)	2.97 (16.9)	3.08 (17.5)	2.97 (16.9)	3.85 (21.9)	3.08 (17.5)
Below grade foundation walls	2.98 (16.2)	2.98 (16.2)	3.46 (19.7)	2.98 (16.2)	3.46 (19.7)	2.98 (16.2)
Unheated floors below frost line	Uninsulated		Uninsulated		Uninsulated	
Exterior walls of an attached garage	3.08 (17.5)	2.97 (16.9)	3.08 (17.5)	2.97 (16.9)	3.85 (21.9)	3.08 (17.5)
Walls adjacent to an unconditioned garage	2.92 (16.6)	2.81 (16.0)	2.92 (16.6)	2.81 (16.0)	3.69 (21.0)	2.92 (16.6)
Unheated floors above frost line	1.96 (11.1)	1.96 (11.1)	1.96 (11.1)	1.96 (11.1)	1.96 (11.1)	1.96 (11.1)
Slabs-on-grade with an integral footing	1.96 (11.1)	1.96 (11.1)	3.72 (21.1)	2.84 (16.1)	3.72 (21.1)	2.84 (16.1)
Heated floors	2.32 (13.2)	2.32 (13.2)	2.84 (16.1)	2.84 (16.1)	2.84 (16.1)	2.84 (16.1)
Skylight shafts	3.08 (17.5)	2.97 (16.9)	3.08 (17.5)	2.97 (16.9)	3.85 (21.9)	3.08 (17.5)
Attic access hatch	2.60 (14.8)	2.60 (14.8)	2.60 (14.8)	2.60 (14.8)	2.60 (14.8)	2.60 (14.8)
Windows, Doors and Skylights	See Page 27					

Figure 6: Minimum required R-Values for construction assemblies in the three climate zones of Alberta. Taken from page 7 of [5]

ii. The Building Code relaxes certain R-Value minimums with the installation of a Heat Recovery Ventilator (HRV). This house does not contain an HRV, so the design uses the most stringent requirements.
iii. The Building Code also supplies requirements for fenestration which are implemented in Appendix A-2.

2.2.6 Wall/Roof Assemblies

Please note that only thermally significant components are specified for the following assemblies. The assemblies do not include taping, vapour barriers, paints, or other non-insulating materials of negligible thickness. The calculation and breakdown of the given R-values for each assembly is given in Appendix A-1.

i. **Above Grade Exterior Walls (Includes walls adjacent to unconditioned garage)**

As shown in 2.2.4, above grade exterior walls must have an R-value of at least 17.5. To achieve this, the following assembly was selected.

- 8” Lapped Wood Bevel Siding
- ¾” Plywood
- 2”x 6” (Nominal) Wooden Studs on 16” Centers
- 5 ½” of Glass-Fiber Batt Insulation between Studs

- ½” Gypsum Wallboard Interior

Total R-Value: 17.74 (Compliant)

ii. **Below Grade Foundation Walls (Includes basement wall above grade)**

Below Grade Foundation Walls require an R-Value of 19.7. To allow simplicity of design and some conservative estimates, the same construction was assumed for basement walls above grade despite the lower R-Value requirement for those assemblies.

- 8” Thick Lightweight Aggregate/Limestone Concrete
- 1 ½” Extruded Polystyrene Insulation (Continuous)
- 2”x 4” (Nominal) Wooden Studs on 24” Centers
- 3 ½” of Glass-Fiber Batt Insulation between Studs
- ½” Gypsum Wallboard Interior

Total R-Value: 19.7 (Compliant)

iii. **Garage Exterior Walls**

The Garage walls require the same minimum R-Value as the other above grade exterior walls. For that reason, this assembly is identical to the one specified in part i.

iv. **Ceiling Assembly**

The ceiling below the unconditioned attic has a high R-Value requirement of 59.2. The following assembly was selected.

- ½” OSB as Attic Flooring
- 1 ½” Extruded Polystyrene Insulation (Continuous)
- 2”x 10” (Nominal) Wooden Joists on 16” Centers
- 9 ½” of Medium Density Polyurethane Foam between studs
- ½” Gypsum Board Ceiling

Total R-Value: 61.73 (Compliant)

v. **Roof Assembly**

The Building Code does not specify minimum R-Values for roofs. For this reason, a simple roof was specified. This is justified by the very high R-Value for the ceiling specified in part iv.

- Black Asphalt Shingles
- 2”x 4” (Nominal) Rafters on 16” Centers

Total R-Value: 2.3

For the purposes of estimating heat losses from the roof/ceiling assembly, the R-Values for roof and ceiling were combined as shown in Appendix A-1.

2.2.7 Fenestration (Doors and Windows)

i. Assume all windows are Triple Glazed with ½" Argon spaces, one surface must have emissivity of 0.2 coating. This is compliant with ASHRAE 90.2 and the Alberta Building Code.
ii. Assume all windows and are operable to be conservative.
iii. Assume the front and back door are insulated steel doors with wooden edge in a wooden frame with 25% glazing. This is compliant with ASHRAE 90.2 and the Alberta Building Code.
iv. Assume the door from house interior to the garage is an insulated steel door with wooden edge in a wooden frame (no glazing). This is compliant with ASHRAE 90.2 and the Alberta Building Code.

2.2.8 House Construction

i. To comply with ASHRAE Standard 62.2 in terms of infiltration rates (Section 2.2.3), the designers have assumed adequate care and effort will be used in construction of this residence to classify it as "Good Construction". This assumption is used to select a value for Infiltration Driving Force (IDF) and Air Change Rate (ACH)
ii. The discharge coefficient is assumed to be CD = 1 [in^2] and the reference pressure difference is assumed to be 0,016 in. wg as per the procedure in Howell et al. Section 6.2.5.
iii. We assume that the attached garage shown in the drawings is insulated according to the Alberta Building Code, but not heated by the system designed. The garage will act as a buffer space with garage temperature equal to the mean of the indoor and outdoor design temperatures. Using the values from Table 1, we assume the garage has a temperature of 27.8°F.

2.2.9 Duct Design and Construction

i. Ducts are assumed to be well constructed with leakage rates of 5%
ii. Ducts are assumed to be well insulated with an insulation rating of R-8
iii. To ensure adequate ventilation and decrease the impact of infiltration, the air flow rate produced by the fan in the duct system will produce 200 cubic feet per minute (cfm). This assumption is made based on Howell et al., and is detailed in Appendix D.
iv. All other assumptions related to the duct system design are included in Appendix D.

3 BUILDING HEATING LOAD ANALYSIS

The total heating load of the building was determined by combining the transmission load with the infiltration, ventilation, and distribution load. At first, the building's wall, roof, doors, etc were designed to have thermal resistances that were compliant to ASHRAE 90.2 and the Alberta Building code. Afterwards, the calculated thermal resistance of the building was multiplied by the area perpendicular to the heat flow and the temperature difference to give the sensible heat loss through these components. Conservative assumptions were made in compliance with ASHRAE Codes and Standards where necessary, such as having the outdoor humidity ratio (W_o) be 0, resulting in a conservative calculated value. This total transmission heat loss was calculated to be approximately 24,000 Btu/h.

Next, the sensible and latent heat losses from infiltration and ventilation were calculated to be a total of approximately 25,000 Btu/h. The infiltration calculations showed that the building experiences a leakage of 82 cfm and the building requires at least 128 cfm of ventilation. Finally, the duct distribution heat loss was taken into consideration for two cases, one being a system with only a furnace, and the second being a system with a furnace and heat pump. It was calculated that the total heat loss (sensible and latent) for these two cases was approximately 54,000 and 56,000 Btu/h, respectively. In the next section, the two of these loads were compared financially to see which yielded the most feasible decision.

Detailed analysis for the total thermal resistance calculation can be found in Appendix A.1, building transmission heating loads in Appendix A.2, infiltration and ventilation heating loads in Appendix A.3, and distribution (duct) loss in Appendix A.4.

4 Economic & Equipment Analysis

4.1 Cost Analysis of Equipment Configuration

The cost implication associated with the use of a heat pump in the residential building in Edmonton shown in in the tables of Appendix E were analyzed using the bin method. The bin method was chosen as opposed to the degree day method as the efficiency and rated output of a heat pump is a function of outdoor temperature. The bin method takes various attainable temperatures during the heating season into consideration while the degree day method assumes the heat pump operates at the same worst scenario temperature difference all year round. Data for Edmonton was taken from the supplementary weather data provided (Edmonton-ASHRAE 2017), which describes the number of hours over the heating season the ambient outdoor temperature was a certain temperature. This data was sorted into temperature “bins”, which were used to evaluate the heat pump performance at each outdoor temperature. The temperature difference between each bin temperature and the balance point temperature (temperature at which no heating or cooling of building is required) was calculated. The Bin method and total heat load (sensible and latent) of the building due to the envelope, infiltration and ventilation heat loss were used to calculate the heat pump supplied heating capacity and the space load. These two parameters are essential in the cost analysis as would be shown later in this section. The space load that cannot be supplied by the heat pump was then to be carried by the gas furnace. Heating value, cost of energy per kwh. Price of electricity, price of natural gas.

Four heat pumps were evaluated from HVAC Fundamentals textbook [1]; These being the XYZ CORP Models A030, A036, A048 and A060, each with a different max heating capacity and rated electrical input required. Heat pump specifications, their operating time and heat supplied, supplementary heat capacity from the natural gas furnace were tabularized and analyzed to obtain the cost associated with running these systems. See Appendix.. For tables and calculation details.

This was done by using the heating value of natural gas, conversion factor from BTU to KWh and the electrical and natural gas prices in Edmonton which were obtained from EPCOR and ATCO websites online. As the capacity of the heat pump increased to better meet the heat demand; its electrical demand also increased which in turn drove the running cost of the combined system up. Conversely, a smaller heat pump provided less heat capacity and relied on the natural gas furnace to provide additional heating, lowering overall electrical dependence and thus lowering overall electrical cost while increasing natural gas costs.

The lifetime cost of this heating system was also calculated for combined performances and only gas furnace performance. Assuming the maintenance costs will be $150.00 (for each visit from technicians) and will increase by 20% for every 3 years. The furnace was assumed to require a maintenance visit once in 3 years. The natural gas price was assumed to increase by 2% every year (due to inflation). These were all done with the 10 years life time cycle for the machine. Comparing only natural gas operation leads to less cost of $8180.71 in comparison to $20362.75 shown in in the last Table of Appendix E. The heat pump also demands more space, so proceeding with the single natural gas furnace will lead to better results rather than adding a heat pump.

4.2 Equipment Selection

4.2.1 Furnace Selection

A Trane S9X2C100U4 with Trane CleanEffects™ furnace was selected for the building because of its:

- Large nominal input capacity of 100,000 [Btuh]
- High 96% AFU Efficiency (Energy Star© Certified)
- Compact design (can fit into tight spaces)
- Quiet operation due to its 2-stage gas heat and insulated cabinet
- Easy installment and serviceability
- Reliable and durable build quality
- Providence of cleaner, healthier indoor air (due to Trane CleanEffects™)
- Infrequent temperature swings, providing consistent temperature outputs

Further information can be found in Appendix C.1 regarding the furnace selection as well as links to the manufacturer and product’s website.

4.2.2 Humidifier Selection

The humidifier selected for the building was an Aprilaire 900 Whole House Steam High Output Humidifier. This humidifier is designed for homes up to 6,200 sq. ft and can provide up to 34.6 gallons per day, which is more than sufficient for the requirements of the building. In addition to meeting the requirements, it does not produce white film or dust and has a dual sensor 24/7 auto mode to continually monitor indoor and outdoor relative humidity.

Further information can be found in Appendix C.2 regarding the humidifier selection as links to the manufacturer and product’s website.

5 RECOMMENDATIONS

- Keep the attic conditioned and unvented with highly insulated layers from indoor. When the attic is unvented, air sealed and with added insulation, it gives us better results in heat conduction through the ceiling. Also, it helps the duct work not to lose the energy when the duct passes through the attic.

- The use of heat pumps is not recommended because the associated costs are about five to six times higher than just using a furnace (from $1326.7 to $1691.95.66 for heat pumps and furnace combination, compared with $274.41 for just using a furnace). Furthermore, use of electric baseboards is not recommended as the cost is more than ten times higher than just using a furnace. Hence for the heating season in Edmonton, a natural gas-based furnace is best suited to minimize running costs at this time.

- With the outdoor humidity ratio assumed to be 0 lb/lb in the calculations, a very strong humidifier was required. Costs of humidifiers can reduced by 10x if a more accurate, and less conservative, approach is done to calculate the mist flow rate that the humidifier needs to provide.

6 References

[1] R. H. Howell et al., *Principles of Heating Ventilating and Air Conditioning*, 8th ed. Atlanta, GA, W. Stephen Comstock.

[2] *Thermal Environmental Conditions for Human Occupancy,* ASHRAE 55, 2017

[3] *Ventilation and Acceptable Indoor Air Quality in Residential Buildings,* ASHRAE 62.2, 2016

[4] *Energy-Efficient Design of Low-Rise Residential Buildings,* ASHRAE 90.2, 2018

[5] *Prescriptive Energy Efficiency Requirements for Houses,* Alberta Building Code Section 9.36, 2016

[6] Tyler Hoyt, Stefano Schiavon, Federico Tartarini, Toby Cheung, Kyle Steinfeld, Alberto Piccioli, and Dustin Moon, 2019, CBE Thermal Comfort Tool. Center for the Built Environment, University of California Berkeley.

[7] “Water - Density, Specific Weight and Thermal Expansion Coefficient.” Engineering ToolBox. Accessed November 29, 2019. https://www.engineeringtoolbox.com/water-density-specific-weight-d_595.html.

[8] McDonald and Magande (Introduction to Thermo-Fluids System Design

Appendix A – Heat Loads

A.1 Thermal Resistances of Building Construction

All Heat Transfer Coefficients for Building Components and Assemblies

The Overall Heat Transfer Coefficient (*U*) of a construction assembly is the inverse of the Thermal Resistance (R-Value) of that assembly:

$$U = \frac{1}{R} \qquad \left[\frac{\mathrm{Btu}}{\mathrm{h\ ft^2\ °F}}\right] \tag{1}$$

To determine these R-Values, provided in Section 2.2.6, the sum of the individual assembly components are combined using their individual Thermal Resistances. These resistances can either be given as an R-Value (as with many standard thickness items), or calculated using Equation 2:

$$R = \frac{x}{k} \qquad \left[\frac{\mathrm{h\ ft^2\ °F}}{\mathrm{Btu}}\right] \tag{2}$$

Where x is the thickness of the component layer (in inches or mm), and k is its thermal conductivity. These values can usually be found in tables or manufacturer specifications. The total R-Value for an assembly is determined as shown in Equation 3:

$$R_{total} = x_{cavity} \sum R_{cavity} + x_{stud} \sum R_{stud} \tag{3}$$

Where:

v. R_{total} is the total R-Value of the assembly
vi. x_{cavity} & x_{stud} are fractional coefficients indicating the proportion of the assembly that is wooden stud or insulated cavity (where applicable). For example, if a wall has wooden studs on 16” centres (16” O.C.), x_{cavity} will be 0.75 and x_{stud} will be 0.25. The sum of these values must be 1.
vii. ΣR_{cavity} & ΣR_{stud} are the summed R-Values of assembly components.

To demonstrate the use of these equations, the R-Value for the basic exterior wall is determined below. After this calculation, the component R-Values for all building assemblies found in 2.2.6 are tabulated below.

R-Value Calculation for Exterior Above Grade Walls:

As shown in Section 2.2.6, the exterior above grade walls for this single-family residence are constructed from:

- Outdoor Air (Or Garage Air)
- 8” Lapped Wood Bevel Siding
- ¾” Plywood
- 2”x 6” (Nominal) Wooden Studs on 16” Centres
- 5 ½” of Glass-Fibre Batt Insulation between Studs
- ½” Gypsum Wallboard Interior
- Indoor Air

As well as the R-Values from the construction components, the air films on both sides of the wall also contribute to its thermal resistance. The resistances for different air film conditions are found in Table 5-12 from Howell et al. (See Figure 7). R-Values for the Wood Bevel Siding and Plywood are found directly in Table 5-15 from Howell et al., (see Figure 8). The R-Values for the Wood Studs, Glass-Fibre Insulation, and Gypsum Wallboard are all calculated using Equation 2. The values for *k* are also given in Table 5-15, indicated for the gypsum wallboard in Figure 8. Using the value from the table, we calculate the R-Value for the gypsum layer:

$$R_{gypsum} = \frac{0.5\ \text{in.}}{1.1\,\frac{\text{Btu in}}{\text{h ft}^2\ °\text{F}}} = 0.45\ \frac{\text{h ft}^2\ °\text{F}}{\text{Btu}}$$

Table 5-12 Surface Film Coefficients/Resistances
(Table 10, Chapter 26, 2017 ASHRAE Handbook—Fundamentals)

		Surface Emittance, ε					
		Non-reflective ε = 0.90		Reflective ε = 0.20		ε = 0.05	
Position of Surface	Direction of Heat Flow	h_i	*R*	h_i	*R*	h_i	*R*
STILL AIR							
Horizontal	Upward	1.63	0.61	0.91	1.10	0.76	1.32
Sloping—45°	Upward	1.60	0.62	0.88	1.14	0.73	1.37
Vertical	Horizontal	1.46	0.68	0.74	1.35	0.59	1.70
Sloping—45°	Downward	1.32	0.76	0.60	1.67	0.45	2.22
Horizontal	Downward	1.08	0.92	0.37	2.70	0.22	4.55
MOVING AIR (Any position)		h_o	*R*				
15 mph Wind (for winter)	Any	6.00	0.17	—	—	—	—
7.5 mph Wind (for summer)	Any	4.00	0.25	—	—	—	—

Notes: (References are to Chapter 26 in the 2013 *ASHRAE Handbook—Fundamentals*)
1. Surface conductance h_i and h_o measured in Btu/h·ft²·°F; resistance *R* in °F·ft²·h/Btu.
2. No surface has both an air space resistance value and a surface resistance value.
3. Conductances are for surfaces of the stated emittance facing virtual blackbody surroundings at the same temperature as the ambient air. Values are based on a surface-air temperature difference of 10°F and for surface temperatures of 70°F.
4. See Chapter 4 in the 2013 *ASHRAE Handbook—Fundamentals* for more detailed information.
5. Condensate can have a significant impact on surface emittance.

Figure 7: Thermal resistances from different air films, taken from [1]

Description	Density, lb/ft^3	Conductivity[b] k, $Btu \cdot in/h \cdot ft^2 \cdot °F$	Resistance R, $h \cdot ft^2 \cdot °F/Btu$	Specific Heat, $Btu/lb \cdot °F$	Reference[l]
Building Board and Siding					
Board					
Asbestos/cement board	120	4	—	0.24	Nottage (1947)
Cement board	71	1.7	—	0.2	Kumaran (2002)
Fiber/cement board	88	1.7	—	0.2	Kumaran (2002)
	61	1.3	—	0.2	Kumaran (1996)
	26	0.5	—	0.45	Kumaran (1996)
	20	0.4	—	0.45	Kumaran (1996)
Gypsum or plaster board	40	1.1	—	0.21	Kumaran (2002)
Oriented strand board (OSB) 7/16 in.	41	—	0.62	0.45	Kumaran (2002)
1/2 in.	41	—	0.68	0.45	Kumaran (2002)
Plywood (douglas fir) 1/2 in.	29	—	0.79	0.45	Kumaran (2002)
5/8 in.	34	—	0.85	0.45	Kumaran (2002)
Plywood/wood panels 3/4 in.	28	—	1.08	0.45	Kumaran (2002)
Vegetable fiber board					
sheathing, regular density 1/2 in.	18	—	1.32	0.31	Lewis (1967)
intermediate density 1/2 in.	22	—	1.09	0.31	Lewis (1967)
nail-based sheathing 1/2 in.	25	—	1.06	0.31	
shingle backer 3/8 in.	18	—	0.94	0.3	
sound-deadening board 1/2 in.	15	—	1.35	0.3	
tile and lay-in panels, plain or acoustic	18	0.4	—	0.14	
laminated paperboard	30	0.5	—	0.33	Lewis (1967)
homogeneous board from repulped paper	30	0.5	—	0.28	
Hardboard					
medium density	50	0.73	—	0.31	Lewis (1967)
high density, service-tempered and service grades	55	0.82	—	0.32	Lewis (1967)
high density, standard-tempered grade	63	1.0	—	0.32	Lewis (1967)
Particleboard					
low density	37	0.71	—	0.31	Lewis (1967)
medium density	50	0.94	—	0.31	Lewis (1967)
high density	62	1.18	0.85	—	Lewis (1967)
underlayment 5/8 in.	44	0.73	0.82	0.29	Lewis (1967)
Waferboard	37	0.63	0.21	0.45	Kumaran (1996)
Shingles					
Asbestos/cement	120	—	0.21	—	
Wood, 16 in., 7 1/2 in. exposure	—	—	0.87	0.31	
Wood, double, 16 in., 12 in. exposure	—	—	1.19	0.28	
Wood, plus ins. backer board 5/16 in.	—	—	1.4	0.31	
Siding					
Asbestos/cement, lapped 1/4 in.	—	—	0.21	0.24	
Asphalt roll siding	—	—	0.15	0.35	
Asphalt insulating siding (1/2 in. bed)	—	—	0.21	0.24	
Hardboard siding 7/16 in.	—	—	0.15	0.35	
Wood, drop, 8 in. 1 in.	—	—	0.79	0.28	
Wood, bevel					
8 in., lapped 1/2 in.	—	—	0.81	0.28	
10 in., lapped 3/4 in.	—	—	1.05	0.28	
Wood, plywood, 3/8 in., lapped	—	—	0.59	0.29	
Aluminum, steel, or vinyl,[h, i] over sheathing				—	
hollow-backed	—	—	0.62	0.29[i]	
insulating-board-backed 3/8 in.	—	—	1.82	0.32	
foil-backed 3/8 in.	—	—	2.96	—	
Architectural (soda-lime float) glass	158	6.9	—	0.21	
Glass fiber[d]					
attics, ~4 to 12 in.	0.4 to 0.5	0.36 to 0.38	—	—	Four manufacturers (2011)
attics, ~12 to 22 in.	0.5 to 0.6	0.34 to 0.36	—	—	Four manufacturers (2011)
closed attic or wall cavities	1.8 to 2.3	0.24 to 0.25	—	—	Four manufacturers (2011)

Figure 8: Thermal properties of building materials, indicating the values for Gypsum board and Wood Bevel Siding used in this project. Taken from [1]

The remaining component R-Values are tabulated below in Table 2 for the stud and cavity components:

Table 2: Tabulated Values for the thermal resistance of specified exterior above grade walls

Exterior Above Grade Walls			
Element	**R (Insulated Cavity)**	**R (Studs)**	**Note:**
Outside Air	0.17	0.17	Table 5-12
Wood Bevel Siding	0.81	0.81	Table 5-15
3/4" Plywood Siding	1.08	1.08	Table 5-15
Wood Stud, 16” O.C., nominal 2x6	-	5.5/0.83 = 4.22	Table 5-15 Page 168
Glass-Fibre Batt Insulation (5.5 in)	5.5/0.32 = 17.19	-	Table 5-15 Page 164
½” Gypsum Wallboard	0.5/1.1 = 0.45	0.5/1.1 = 0.45	Table 5-15
Indoor Air	0.68	0.68	Table 5-12
Subtotal	20.38	9.82	
Total Wall R-Value	17.74		
Wall U-Value (Exterior)	0.06		
Wall U-Value to Unheated Garage	0.05		

The individual components are summed for the cavity and stud portions of the wall. Note that certain elements only appear in either “cavity” or “stud” but not both. Using the subtotal column, the total R-Value for the wall assembly is calculated as follows:

$$R_{exteriorwall} = (0.75)R_{cavity} + (0.25)R_{stud}$$

$$R_{exteriorwall} = (0.75)(20.38) + (0.25)(9.82)$$

$$\boldsymbol{R_{exteriorwall} = 17.74}$$

The Overall Heat Transfer Coefficient (*U*) for the wall is calculated by taking the inverse of this R-Value, shown in the table above. Note that the exterior wall assembly (and some of the other assemblies) have additional U-Values calculated for other cases, such as bordering the unheated garage.

Using the same procedure for each assembly, the R-values for all construction assemblies are included below:

Below Grade Foundation Walls (Includes basement wall above grade)

Table 3: Tabulated Values for the thermal resistance of basement foundation wall

Basement Foundation Wall			
Element	**R (Insulated Cavity)**	**R (Studs)**	**Note:**
Outside Air	0.17	0.17	Table 5-12
Concrete Wall (8")	1.60	1.60	Taking Conductivity as 5.0 from Table 5-15 Lightweight aggregate or limestone concrete
Extruded Polystyrene 1.5"	1.5/0.2 = 7.50	1.5/0.2 =7.50	Table 5-15 Page 164
Wood Stud 24" O.C., nominal 2x4	-	3.5/0.83 = 4.22	Table 5-15 Page 168
Glass-Fibre Batt Insulation (3.5")	3.5/0.32 = 10.94	-	Table 5-15 Page 164
½" Gypsum Wallboard	0.5/1.1 = 0.45	0.5/1.1 = 0.45	Table 5-15 Page 165
Indoor Air	0.68	0.68	Table 5-12
Subtotal	21.34	14.62	
Total Wall R-Value (Above Grade)	**19.86**		
Above Grade U-Value	**0.05**		

The U-Value for the walls below grade is not calculated using this procedure. The U-Value for the below-grade basement walls and basement floor is determined using Table 6-18 in Howell et al., assuming 7 ft depth and R-15 insulation.

U-Value Below Grade: 0.043

The U-Value for the basement floor is taken from Table 6-19 in Howell et al., with a depth of 7 ft and a minimum width of 32 ft.

U-Value Basement Floor: 0.026

Garage Exterior Walls

Table 4: Tabulated Values for the thermal resistance of garage walls

Garage Walls			
Element	**R (Insulated Cavity)**	**R (Studs)**	**Note:**
Outside Air	0.17	0.17	Table 5-12
Wood Bevel Siding	0.81	0.81	Table 5-15 Page 165
3/4" Plywood Siding	1.08	1.08	Table 5-15 Page 165
Wood Stud 16” O.C., nominal 2x6	-	5.5/0.83 = 6.3	Table 5-15 Page 168
Glass-Fibre Batt Insulation (5.5 in)	17.19	-	Table 5-15 Page 164
½” Gypsum Wallboard	0.45	0.45	Table 5-15 Page 165
Indoor Air	0.68	0.68	Table 5-12
Subtotal	20.38	9.82	
Total Wall R-Value	**17.74**		
Wall U-Value	**0.06**		

Ceiling Assembly

Table 5: Tabulated Values for the thermal resistance of ceiling assembly

Ceiling			
Element	**R (Insulated Cavity)**	**R (Joists)**	**Note**
Attic Air	0.92	0.92	Table 5-12
1/2" OSB	0.68	0.68	Table 5-15 Page 165
1" Extruded Polystyrene	5	5.00	
2x10 Joists 16" O.C.	-	9.5/0.83 = 11.45	Table 5-15 Page 168
9.5" medium density polyurethane foam	67.86	-	Table 5-15
Gypsum Board	0.45	0.45	
Indoor Air	0.92	0.92	Table 5-12
Subtotal	75.83	19.42	
Ceiling R-Value:	**61.73**		

Roof Assembly

Table 6: Tabulated Values for the thermal resistance of the roof assembly

Roof			
Element	**R (Insulated Cavity)**	**R (Rafts)**	**Note**
Outdoor Air	0.17	0.17	Table 5-12
Black Asphalt Shingles	0.44	0.44	Table 5-15 Page 166
2x4 Rafts 16" O.C.	-	3.5/0.83 = 4.38	Table 5-15 Page 168
Attic Air	0.76	0.76	Table 5-12
Subtotal	1.37	5.75	
Roof R-Value	**2.33**		

The Roof/Ceiling combined R-Value was calculated using the following equation:

$$R_{rc} = R_c + \frac{R_r}{n}$$

Where:

$$n = \frac{A_{roof}}{A_{ceiling}}$$

Table 7: Tabulated values for the combined roof and ceiling assembly

Roof/Ceiling Combined R-Value:	**63.92**
Roof/Ceiling Combined U-Value:	**0.016**

U-Values for Fenestration

All doors and windows were selected to comply with the Alberta Building Code. That standard listed a maximum USI (metric U-Value) of 1.6. Converting to Imperial U-Value, this corresponds to a maximum U-value of 0.28. Using Table 6-16 and 6-17 in Howell et al., the following doors and windows were selected.

Doors ([1] Table 6-17)

Front Door and Back Door: Insulated steel door with wooden edge in a wooden frame. 25% glazing.

U-Value: 0.26

Interior Garage Door: Insulated steel door with wooden edge in wooden frame. No glazing.

U-Value: 0.16

Windows ([1] Table 6-16)

All windows assumed to be triple-glazed, with ½" argon spaces. One pane of glass must have a reflective coating with emissivity e = 0.2.

U-Value: 0.27

A.2 HEATING LOADS FROM BUILDING TRANSMISSION

The heat transfer coefficients determined in Appendix A-1 are used to find the heat lost through the building walls, roof, etc. The heat lost through transmission is calculated using:

$$q = UA\Delta T \qquad \left[\frac{\text{Btu}}{\text{h}}\right] \tag{4}$$

Where:

- *q* is the heat loss
- *U* is the overall heat transfer coefficient
- *A* is surface area
- *ΔT* is the temperature difference across the assembly

To find the transmission losses, the building is modelled as a box as shown in Figure 9.

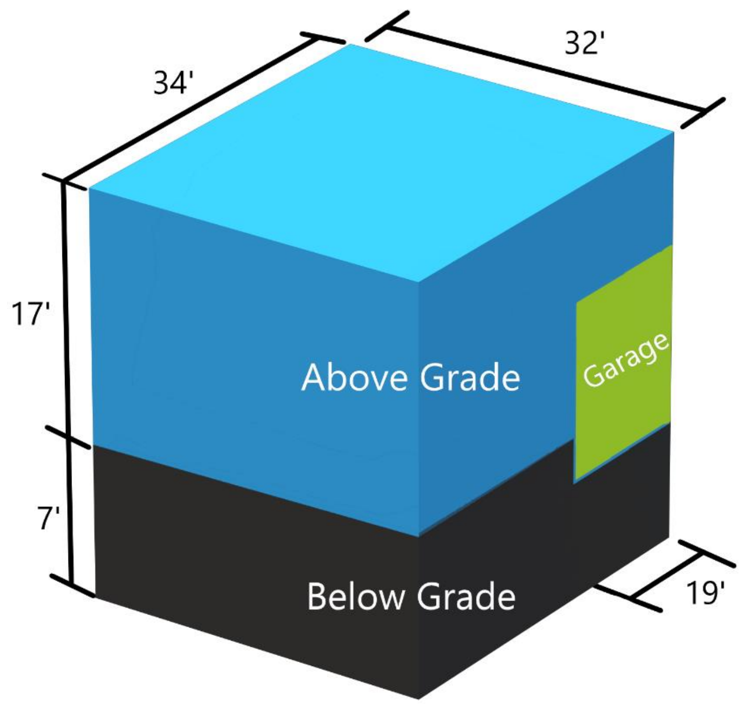


Figure 9: Simplified representation of the single-family home

The total surface area of all walls is calculated as:

$$SA = 2\big((34\text{ ft} \cdot 24\text{ ft}) + (32\text{ ft} \cdot 24\text{ ft})\big) = 3168\text{ ft}^2$$

The surface area of ceiling is:

$$SA_{ceiling} = (34\ \text{ft}^2 \cdot 32\ \text{ft}^2) = 1088\ \text{ft}^2$$

The basement floor has the same surface area as the ceiling (1088 ft^2).

Table 8: Gross surface area of the single-family residence, broken into walls, floor, and ceiling exposed to outdoor conditions.

Item	Gross Surface Area (ft^2)
Walls	3,168
Ceiling	1,088
Floor	1,088

These gross areas do not include the impact of below grade walls, doors, windows, and buffer spaces (such as wall shared with the garage shown in Figure 9 above). Each of these items impacts the heat transfer coefficient from the building. In Table 4 below, the different areas of the exterior envelope are broken up as shown in the architectural drawings provided in Section 1. Each area of the envelope has a corresponding U-Value and Temperature Difference. The U-Values are determined/selected in Appendix A-2 and re-tabulated in Table 4 below. The temperature differences (determined from the outdoor design temperatures provided in Section 2) are also tabulated in Table 4. Using these different areas, the total heat loss from Transmission is determined to be **23,992.7 Btu/h.**

Table 9: Thermal losses from all contributing exterior walls, ceilings, and fenestration.

Component	U (Btu/h ft^2 °F)	ΔT (°F)	Area (ft^2)	Sensible (Btu/h)
Gross Exposed Walls and Partitions	-	-	3168	-
Windows	0.270	84.4	336	7656.8
Doors	0.260	84.4	42	921.6
Wall Areas Adjacent to Buffer Space	0.048	42.2	131	264.6
Interior Door to Garage	0.160	42.2	21	141.8
Foundation Wall Above Grade	0.050	84.4	19	80.7
Foundation Wall Below Grade	0.043	78.7	924	3200.4
Net Exposed Walls and Partitions	0.056	84.4	1695	8063.3
Basement Floor	0.026	78.7	1088	2226.8
Ceilings and Roofs	0.016	84.4	1088	1436.6
Total Transmission Heat Loss				**23992.7**

A.3 HEATING LOADS FROM INFILTRATION & VENTILATION

Infiltration:

To determine the infiltration flow rate, the following equation is used

$$Q_i = A_L * IDF \tag{5}$$

Where,

- A_L is the building effective leakage area (including flue) at reference pressure difference of 0.016 in. of water, assuming discharge coefficient CD = 1 [in^2].
- *IDF* is the infiltration driving force in [cfm/in^2].

With

$$A_L = A_{es} * A_{ul} \tag{6}$$

Where,

- A_{es} is the building exposed surface area [ft^2]
- A_{ul} is the leakage area [in^2/ft^2]

Table 6-3 Unit Leakage Areas

(Table 3, Chapter 17, 2017 ASHRAE Handbook—Fundamentals)

Construction	Description	A_{ul} (in.^{2}/ft^2)
Tight	Construction supervised by air-sealing specialist	0.01
Good	Carefully sealed construction by knowledgeable builder	0.02
Average	Typical current production housing	0.04
Leaky	Typical pre-1970 houses	0.08
Very leaky	Old houses in original condition	0.15

A_{ul} = 0.02 [in.^{2}/ft^2]

Table 6-4 Evaluation of Exposed Surface Area
(Table 4, Chapter 17, 2017 ASHRAE Handbook—Fundamentals)

Situation	Include	Exclude
Ceiling/roof combination (e.g., cathedral ceiling without attic)	Gross surface area	
Ceiling or wall adjacent to attic	Ceiling or wall area	Roof area
Wall exposed to ambient	Gross wall area (including fenestration area)	
Wall adjacent to unconditioned buffer space (e.g., garage or porch)	Common wall area	Exterior wall area
Floor over open or vented crawlspace	Floor area	Crawlspace wall area
Floor over sealed crawlspace	Crawlspace wall area	Floor area
Floor over conditioned or semiconditioned basement	Above-grade basement wall area	Floor area
Slab floor		Slab area

In compliance to the table above, the garage exterior wall areas and roof areas are excluded.

Thus,

$$A_{es} = 2(34 * 17) + 2(32 * 17) + (32 * 34) = 3332 \text{ [ft}^2\text{]}$$

Using Equation 10,

$$A_L = 0.02 * 3332 = 66.64 \text{ [in}^2\text{]}$$

Now calculating IDF with outdoor dry bulb temperature = -14.4 [°F]

Table 6-5 Typical IDF Values, cfm/in.^{2}

(Table 5, Chapter 17, 2017 ASHRAE Handbook—Fundamentals)

	Heating Design Temperature, °F					Cooling Design Temperature, °F		
H, ft	**–40**	**–20**	**0**	**20**	**40**	**85**	**95**	**105**
8	1.40	$\boxed{1.27}$	$\boxed{1.14}$	1.01	0.88	0.41	0.48	0.55
10	1.57	1.41	1.25	1.09	0.92	0.43	0.52	0.61
12	1.75	1.55	1.36	1.16	0.97	0.45	0.55	0.66
14	1.92	1.70	1.47	1.24	1.02	0.47	0.59	0.71
16	2.10	1.84	1.58	1.32	1.06	0.48	0.62	0.76
18	2.27	1.98	1.69	1.40	1.11	0.50	0.66	0.82
20	2.45	2.12	1.80	1.48	1.15	0.52	0.69	0.87
22	2.62	2.27	1.91	1.55	1.20	0.54	0.73	0.92
24	2.80	2.41	2.02	1.63	1.24	0.55	0.76	0.98

H, the building average stack height is simply given by the equation:

$$H = \frac{V_{conditioned}}{A_{conditioned}} = \frac{32 * 34 * 24}{32 * 34 * 3} = 8\ [\mathrm{ft}]$$

Interpolation:

$$IDF_{8,-14.4} = \frac{(-14.4 - 0)}{(-20 - 0)}(1.27 - 1.14) + 1.14 = 1.2336$$

Thus,

$$IDF = 1.2336\ \left[\frac{\mathrm{cfm}}{\mathrm{in}^2}\right]$$

Using Equation 5, the infiltration flow rate is calculated

$$Q_i = 66.64 * 1.2336 = 82.207[\mathrm{cfm}]$$

Note that according to ASHRAE 62.2, this Q_i must be less than two-thirds the value of total ventilation required determined later.

Heat Loss due to Infiltration:

The sensible heat loss due to infiltration is:

$$q_{si} = Q_i * 60 * 0.075 * (0.24 + 0.45\Delta W) * \Delta T \tag{7}$$

With ΔW ~ 0.01 lb/lb in many air-conditioning problems, Equation 37 is approximated by

$$q_{si} = 1.1 * Q_i * \Delta T \tag{8}$$

Where,

- q_{si} is the sensible heat lost [Btu/h]
- ΔT is the dry-bulb indoor and outdoor design temperature [°F]
- Q_i is the infiltration rate [cfm]

Therefore,

$$q_{si} = 1.1 * (82.207\ [\text{cfm}]) * \big(70 - (-14.4)\big)\ °\text{F} = 7632.09788\ \left[\frac{\text{Btu}}{\text{h}}\right]$$

So the total sensible heat lost due to infiltration is:

$$q_{si} = 7632\ \left[\frac{\text{Btu}}{\text{h}}\right]$$

The latent heat loss due to infiltration is:

$$q_{li} = 4840 * Q_i * \Delta W \tag{9}$$

Where,

- q_{li} is the latent heat lost [Btu/h]
- ΔW is indoor and outdoor design humidity ratio difference [lb/lb]

Thus,

$$q_{li} = 4840 * (82.207\ [\text{cfm}]) * (0.005)\left[\frac{\text{lb}}{\text{lb}}\right] = 1989.4094\ \left[\frac{\text{Btu}}{\text{h}}\right]$$

So the total latent heat lost due to infiltration is:

$$q_{li} = 1910 \left[\frac{\text{Btu}}{\text{h}}\right]$$

Ventilation:

The minimum whole-building ventilation rate is given by ASHRAE Standard 62.2-2016

$$Q_V = 0.03A_{cf} + 7.5(N_{br} + 1) \tag{10}$$

Where,

- A_{cf} is the building conditioned floor area [ft^2]
- N_{br} is the number of bedrooms

The building being designed has 2 ordinary bedrooms and 1 master bedroom.

Furthermore, the building has 3 conditioned floor areas of 32’ by 34’.

Therefore Equation 10 becomes,

$$Q_V = 0.03(3 * 32[\text{ft}] * 34[\text{ft}]) + 7.5(3 + 1)$$

$$Q_V = 127.92\ [\text{cfm}]$$

To ensure that infiltration meets the requirements given in ASHRAE 62.2, we take two-thirds of this value and compare that to the Q_i calculated earlier.

$$\frac{2}{3}Q_v = 85.28\ \text{cfm} > Q_i$$

We determine that infiltration meets the requirements given in ASHRAE 62.2.

Energy required to heat outdoor air:

Similar to infiltration, the sensible and latent heat required for ventilation is given by

$$q_{sv} = 1.1 * Q_v * \Delta T \tag{11}$$

And

$$q_{lv} = 4840 * Q_v * \Delta W \tag{12}$$

For sensible heat, Equation 11 becomes:

$$q_{sv} = 1.1 * 127.92 * 84.4$$

$$q_{sv} = 11876.09 \left[\frac{\text{Btu}}{\text{h}}\right]$$

For latent heat, Equation 12 becomes:

$$q_{lv} = 4840 * 127.92 * 0.005$$

$$q_{lv} = 3095.66 \left[\frac{\text{Btu}}{\text{h}}\right]$$

Heat loss due to Infiltration and Ventilation:

Assuming balanced supply and exhaust flow rates, the total sensible and latent heat required from the infiltration and ventilation is simply the sum of the two separately as shown in Equation 13 and 14.

$$q_s = q_{sv} + q_{si} \tag{13}$$

$$q_l = q_{lv} + q_{li} \tag{14}$$

Thus,

$$q_s = 11876.09 + 7632.098 = 19508.19 \left[\frac{\text{Btu}}{\text{h}}\right]$$

$$q_l = 1989.04 + 3095.66 = 5085.70 \left[\frac{\text{Btu}}{\text{h}}\right]$$

So, the total sensible and latent heat loads are:

$$q_s = 19508.2 \left[\frac{\text{Btu}}{\text{h}}\right]$$

$$q_l = 5085.7 \left[\frac{\text{Btu}}{\text{h}}\right]$$

A.4 HEATING DISTRIBUTION (DUCT) LOSS

To calculate the total distribution sensible heat loss, the following equation was used,

$$q_{sdist} = F_{dl} * \Sigma q \tag{15}$$

Where,

- q_{sdist} is the heat lost through distribution in the ducts
- F_{dl} is the duct loss factor (Table 6-16 , Howell et al., pg. 198)
- Σq is the total building heat load calculated from the sum of the sensible and latent heat losses from the transmission, ventilation, and infiltration of the building.

To determine the duct loss factors, two following assumptions were made:

- ducts are well constructed with a leakage rate of 5%
- ducts are well insulated with an insulation rating of R-8

With the attic being the only unconditioned space containing ductwork, it is the only area that requires the calculation of distribution losses.

Table 6-16 Typical Duct Loss/Gain Factor

		1 Story						2 or More Stories					
	Supply/Return Leakage	**11%/11%**			**5%/5%**			**11%/11%**			**5%/5%**		
Duct Location	**Insulation $ft^2 \cdot h \cdot °F/Btu$**	**R-0**	**R-4**	**R-8**	**R-0**	**R-4**	**R-8**	**R-0**	**R-4**	**R-8**	**R-0**	**R-4**	**R-8**
Conditioned space		No loss (F_{dl} = 0)											
Attic	C	1.26	0.71	0.63	0.68	0.33	0.27	1.02	0.66	0.60	0.53	0.29	0.25
	H/F	0.49	0.29	0.25	0.34	0.16	0.13	0.41	0.26	0.24	0.27	0.14	0.12
	H/HP	0.56	0.37	0.34	0.34	0.19	0.16	0.49	0.35	0.33	0.28	0.17	0.15
Basement	C	0.12	0.09	0.09	0.07	0.05	0.04	0.11	0.09	0.09	0.06	0.04	0.04
	H/F	0.28	0.18	0.16	0.19	0.10	0.08	0.24	0.17	0.15	0.16	0.09	0.08
	H/HP	0.23	0.17	0.16	0.14	0.09	0.08	0.20	0.16	0.15	0.12	0.08	0.07
Crawlspace	C	0.16	0.12	0.11	0.10	0.06	0.05	0.14	0.12	0.11	0.08	0.06	0.05
	H/F	0.49	0.29	0.25	0.34	0.16	0.13	0.41	0.26	0.24	0.27	0.14	0.12
	H/HP	0.56	0.37	0.34	0.34	0.19	0.16	0.49	0.35	0.33	0.28	0.17	0.15

Values calculated for ASHRAE Standard 152 default duct system surface area using model of Francisco and Palmiter (1999). Values are provided as guidance only; losses can differ substantially for other conditions and configurations. Assumed surrounding temperatures:

Cooling (C): t_o = 95°F, t_{attic} = 120°F, t_b = 68°F, t_{crawl} = 72°F   Heating/furnace (H/F) and heating/heating pump (H/HP): t_o = 32°F, t_{attic} = 32°F, t_b = 64°F, t_{crawl} = 32°F

Therefore, F_{dl} *(H/F)* = 0.12 and F_{dl} *(H/HP)* = 0.15

From earlier calculations, the following table is a summary for convenience and is used for the calculation of Σq.

Table 10: Summary of heat losses

Component	Heat Loss (Btu/h)
Transmission Losses	23992.7
Ventilation Sensible Loss	11876.09
Ventilation Latent Loss	3095.664
Infiltration Sensible Loss	7632.10
Infiltration Latent Loss	1989.41

Therefore,

$$\Sigma q = 23992.7 + 11876.09 + 3095.664 + 7632.10 + 1989.41 = 48585.97$$

Using Equation 5, for the Heating/Furnace calculation (using $F_{dl}(H/F)$):

$$q_{dist,H/F} = 0.12 * 48585.97 = 5830.32 \left[\frac{\text{Btu}}{\text{h}}\right]$$

Using Equation 5, for the Heating/Heating Pump calculation (using $F_{dl}(H/HP)$):

$$q_{dist,H/HP} = 0.15 * 48585.97 = 7287.89 \left[\frac{\text{Btu}}{\text{h}}\right]$$

The final sum is simply 48585.97 [Btu/h] added by these values.

For the furnace,

$$\Sigma q_F = 5830.32 + 48585.97 = \mathbf{54416.29} \left[\frac{\mathbf{Btu}}{\mathbf{h}}\right]$$

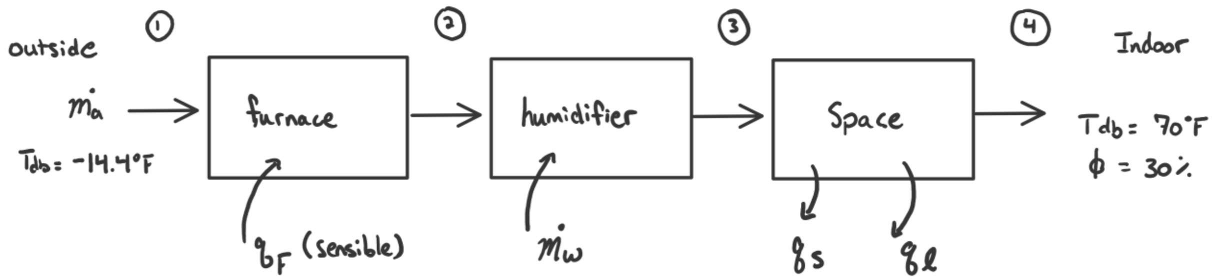
For the heat pump and furnace,

$$\Sigma q_{HP} = 7287.89 + 48585.97 = \mathbf{55873.87} \left[\frac{\mathbf{Btu}}{\mathbf{h}}\right]$$

APPENDIX B – HUMIDIFICATION OPERATION REQUIREMENTS

The humidifier in Appendix C.2's criteria is primarily selected from the provided rate of mist [lb/hour] required to achieve the indoor design condition. This section calculates for this. The following figure is a simple representation of the building HVAC system.

Table 11: Simple Representation of Building HVAC System



To find $\dot{m}_w$, first, a conservation of mass analysis is done.

For air:

$$\dot{m}_a = \text{constant} \tag{16}$$

For water (across the humidifier):

$$\dot{m}_a w_2 + \dot{m}_w = \dot{m}_a w_3 \tag{17}$$

And so

$$\dot{m}_w = \dot{m}_a (w_3 - w_2) \tag{18}$$

Now, indoor properties are found from the Psychometric Chart.

$$v(T_{db} = 70[°\text{F}], \varphi = 30[\%]) = 13.4 \left[\frac{\text{ft}^3}{\text{lb}}\right]$$

And

$$w_4(T_{db} = 70[°\text{F}], \varphi = 30[\%]) = 0.00471 \left[\frac{\text{lb}}{\text{lb}}\right]$$

Using the specific volume, the mass flow rate of air $\dot{m}_a$ is calculated

$$\dot{m}_a = \frac{Q}{v} \tag{19}$$

Where *Q* is the volumetric flow rate value of 200 [cfm] in accordance to Assumption 2.2.9.iii.

Therefore,

$$\dot{m}_a = \frac{200\left[\frac{\mathrm{ft}^3}{\mathrm{min}}\right]}{13.4\left[\frac{\mathrm{ft}^3}{\mathrm{lb}}\right]} * \frac{60[\mathrm{min}]}{1[\mathrm{hour}]} = 895.522\ \left[\frac{\mathrm{lb}}{\mathrm{h}}\right]$$

Because the furnace only provides sensible heat, the humidity ratio across the furnace is the same.

$$w_1 = w_2$$

In accordance to Assumption 2.2.2.iv, the humidity ratio of outdoors was assumed to be a conservative value of 0 [lb/lb].

The last thing required is to calculate the humidity ratio after the humidifier w_4.The latent heat loss at the space is used to calculate this since it is the only heat loss that contributes to change in humidity ratio.

An energy balance of latent energy is as follows

$$\dot{m}_a w_3 h_{fg3} = q_l + \dot{m}_a w_4 h_{fg4} \tag{20}$$

Where q_l is the latent heat lost due to transmission, infiltration, and ventilation. This was calculated to be 5695.28 [Btu/h] in Appendix A.

Which simplifies to the estimation

$$q_l = 4840Q(w_3 - w_4) \tag{21}$$

Solving for w_3,

$$w_3 = \frac{q_l}{4840Q} + w_4 \tag{22}$$

$$w_3 = \frac{5695.28}{4840(200)} + 0.00471 = 0.0106\ \left[\frac{\mathrm{lb}}{\mathrm{lb}}\right]$$

Finally, Equation 22 is used to calculate the required mist flow rate from the humidifier to achieve indoor design conditions.

$$\dot{m}_w = \left(895.522\ \left[\frac{\text{lb}}{\text{h}}\right]\right)\left(0.0106\ \left[\frac{\text{lb}}{\text{lb}}\right] - 0\ \left[\frac{\text{lb}}{\text{lb}}\right]\right)$$

$$\dot{m}_w = 9.49\ \left[\frac{\text{lb}}{\text{h}}\right]$$

APPENDIX C – EQUIPMENT SELECTION

C.1 FURNACE SELECTION

A decision matrix was used to choose between two Trane furnace models.

Table 12: Furnace Selection Decision Matrix

	Furnace Selection						
	Criteria						
	Capacity	**Efficiency**	**Durability**	**Compatibility & Convenience**	**Cost**		
Rating	10	10	10	10	10		
TRANE S9X2C100U4	10	9	8	8	8		
TRANE TUC1C100A9481A	10	7.5	7.5	5	10		
Weighting	35	15	25	5	20	**Total**	**Ranking**
TRANE S9X2C100U4	350	135	200	40	160	885	1
TRANE TUC1C100A9481A	350	112.5	187.5	25	200	875	2

Both Trane units had a nominal capacity of more than 90,000 [Btuh], which is more than enough for the building design's loads as well as superior build quality being made from stainless steel. However, besides the cheaper cost of the TUC1C100A9481A (referred to as XB90 from now on), the S9X2 is superior in every criterion. For efficiency, the S9X2 is Energy Star© certified and has an AFU Efficiency of 96% while the XB90 is not Energy Star© certified and has a lower AFUE of 92.1%. For durability, both units are made of stainless steel but the S9X2 has secondary heat exchangers making it more reliable and durable. The S9X2 is superior with compatibility and convenience due to its dealer friendly design, 2 stage gas heat which results in quieter operation and more consistent temperature output, as well as its compact design allowing it to fit in tighter places. The S9X2 is expected to be between $3,200 to $5,200.

The following is the specifications of the Trane S9X2C100U4:

Table 13: Trane S0X2C100U4 Specifications taken from https://www.trane.com/residential/en/products/gas-furnaces/s9x2/

Model	Max Input Btuh	Nominal Tons Cooling Airflow	Poise	AFUE	Energy Star

S9X2C100U4	100,000	4	Upflow / Horizontal	96	Yes

The specifications for these two furnaces are found at:

https://www.trane.com/residential/en/products/gas-furnaces/s9x2/
https://www.trane.com/residential/en/products/gas-furnaces/xb90/#product-detailsC.2 Humidifier Selection

As calculated in Appendix B, the mist flow rate from the humidifier to achieve indoor design conditions is

$$\dot{m_w} = 9.49 \left[\frac{\mathrm{lb-m}}{\mathrm{h}}\right]$$

Using the density of water at 70 [°F] to be 62.3 [lb-m/ft^3] (taken from [7]).

This value is converted to gallons/day:

$$\dot{m_w} = 9.49 \left[\frac{\mathrm{lb-m}}{\mathrm{h}}\right] * \frac{24\ [\mathrm{h}]}{1\ [\mathrm{day}]} * \frac{1\ [\mathrm{ft}^3]}{62.3[\mathrm{lb-m}]} * \frac{7.48052\ [\mathrm{gallons}]}{1\ [\mathrm{ft}^3]}$$

Thus,

$$\dot{m_w} = 27.35 \left[\frac{\mathrm{gallons}}{\mathrm{day}}\right]$$

A humidifier was searched to be able to support this mist flow rate and have a home area design of around 2000 sq. ft. Since the conservative outside humidity ratio of 0 was assumed in accordance to Assumption 2.2.2.iv, this flow rate required from the humidifier was rather large for a ~2000 sq.ft home and limited the available options. By looking for humidifiers designed for bigger homes, the Aprilaire 800 Whole Steam Humidifier was selected. This humidifier is designed for homes up to 6,200 sq. ft and can provide up to 34.6 gallons per day. The cost for a similar humidifier is around $1,000 on amazon: https://www.amazon.ca/dp/B00R3G57CU?slotNum=0&linkCode=g12&imprToken=E7d.R9pC3kNyWcG3DG94AA&creativeASIN=B00R3G57CU&tag=comfyo-20

Aprilaire 800 Whole House Steam Humidifier, High Output Humidifier

FIND A PRO

- **BUY WITH CONFIDENCE** This high output steam humidifier was designed with electrode technology and manufactured in the U.S.A. by Aprilaire – the inventor of the whole home evaporative humidifier, and the leader in indoor air quality solutions
- **FULL COVERAGE** up to 6,200 square feet in tightly built homes. Choose from 6 levels of output adding 11.5 to 34.6 gallons of moisture into the air per day based on voltage and installation
- **IDEAL FOR** homes in arid, desert climates
- **PURIFIED WATER NOT REQUIRED** Electrode technology requires impurities in the water to promote the transfer of electricity. Water filtration is not recommended – minimizing installation complexity and operating costs
- **NO WHITE FILM OR DUST** is left behind for you to clean up like other steam humidifiers. Aprilaire humidifier just provide clean, humidified air
- **DUAL SENSOR 24/7 AUTO MODE** continually monitors and responds to both outdoor temperature and indoor relative humidity to deliver optimum humidity throughout the home – simply set it and forget it
- **CONVENIENT DIGITAL CONTROL** shows percent humidity, lights indicate humidifier is running and when service is needed, and Blower Activation switch sets humidifier to run continually, or only when the furnace runs
- **HUMIDITY FOR HEALTH** Aprilaire Humidifiers can help you maintain optimal humidity in your home of 35% – 45% which has been shown to reduce the incidence of respiratory infections and symptoms related to allergies and asthma by minimizing the formation of bacteria and viruses, fungi, and dust mites. In addition, you'll feel more comfortable while also preserving items in your home susceptible to damage from changing humidity or dry conditions

Figure 10: Aprilaire 865 Product Information from https://shop.aprilaire.com/products/aprilaire-model-800-humidifier?_ga=2.10729783.2036792618.1575020802-2017819431.1575020802

APPENDIX D – DUCT SYSTEM DESIGN

To complement the designed heating system, the designers have also included the following rectangular duct system to be used with the furnace. The skeleton drawings of these ducts has been overlaid on the architectural drawings of the single-family residence for clarity. This design places the furnace in the basement, with risers ascending through non-critical areas of the residence (the study room and a single corner of one bedroom). The following assumptions were developed to perform detailed design of this system.

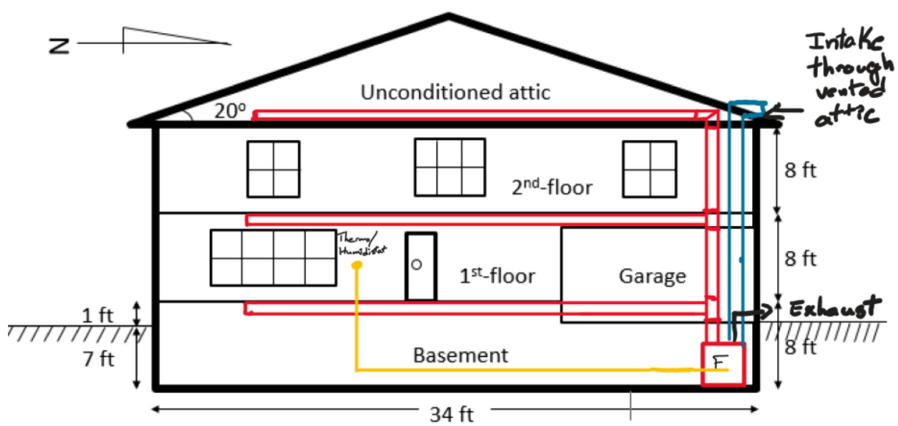


Figure 11: Elevation drawing indicating Risers and thermostat location

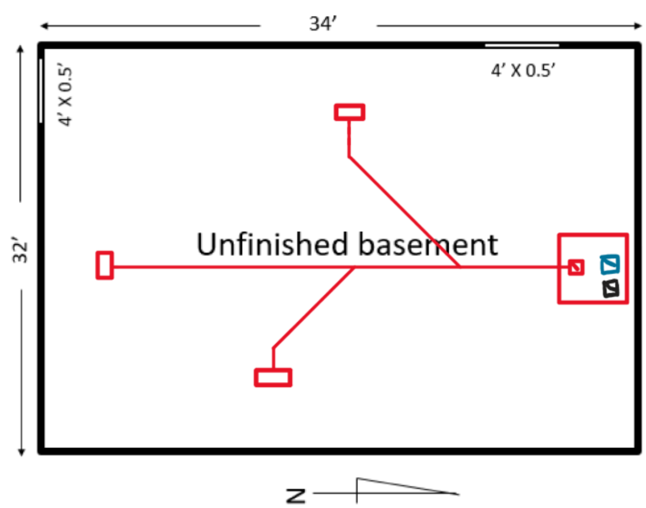


Figure 12: Basement Mechanical Layout including furnace position

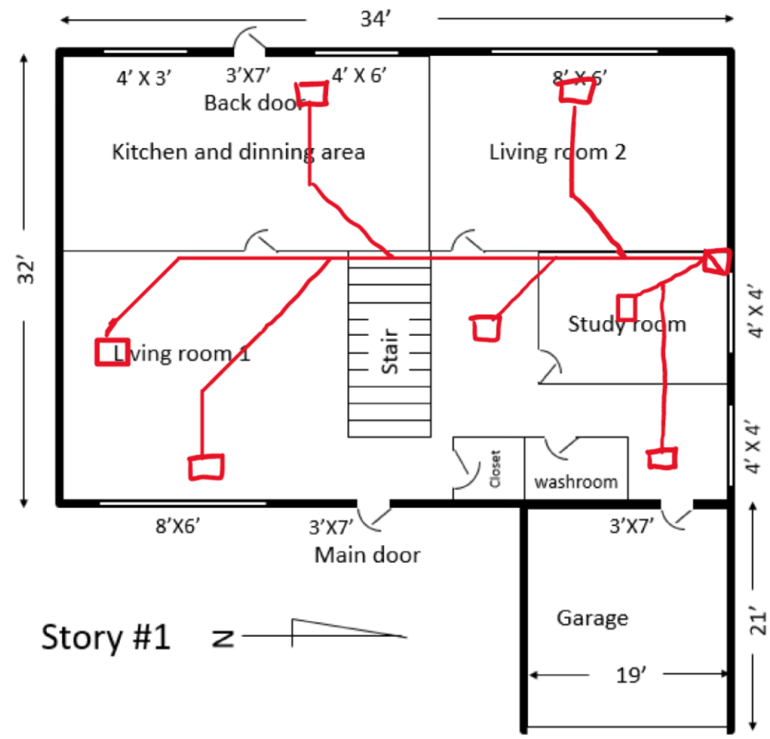


Figure 13: First Floor Mechanical Layout

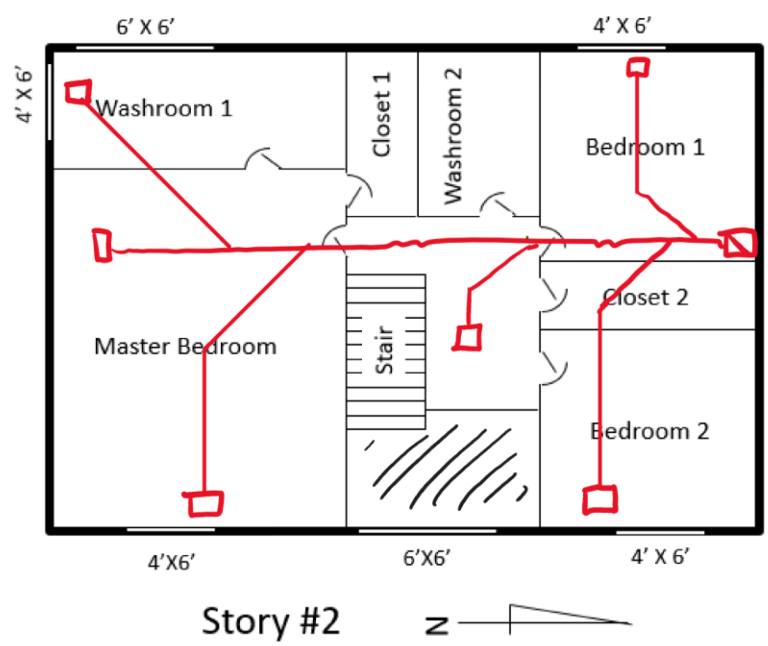


Figure 14: Second Floor Mechanical Layout

Assumptions:

i. This duct system is designed for a residential building, requiring low-velocity, low noise airflow. Air velocity is assumed to be *less than 1200 fpm* in main ducts and *less than 800 fpm* in branches and risers.
ii. As stated in Section 2.2.9.iii, the total airflow provided to the house is assumed to be 200 cfm. This assumption is based on Table 6.2.2.1 in ASHRAE Standard 62.1, indicating minimum ventilation rates in breathing zones. This table (Shown in Howell et al. as Table 5-9) provides ventilation rates per area and per person. The process used to obtain this assumption is detailed below.
iii. In accordance with Assumption ii. above, all diffusers shown in the figures above and below will provide air at a rate of 10 cfm. **The exception to this assumption is that any diffusers in a bedroom will provide 20 cfm.**
iv. As shown on the figures above, the furnace is located in the basement, with the air intake being drawn from the vented attic space.
v. Any supply ducts for a given floor are located in the ceiling of that floor (for example, the ducts providing heating to the 2nd floor are located within the attic.
vi. Any return ducts are located in the floor space of a given floor. The return air system is assumed to be a simple exhaust system, relying on exfiltration and proper damper selection to allow air to exhaust to the outside.
vii. Ducts are assumed to be constructed from galvanized steel as is typical in air distribution systems.
viii. The ducts for this project are assumed to be round as the small flow rates will allow for sufficiently small ducts.
ix. No air will be recirculated in this design (all supply air will be Outdoor Air (OA)).
x. Bathroom and Kitchens will have appropriate external ventilation as specified in ASHRAE 62.2.
xi. Friction losses will be assumed close to the industry standard of 0.1”wg per 100 ft.
xii. All branch fittings are 45° Wyes unless otherwise indicated, and any 90° bends will be mitered with interior vanes.
xiii. All diffusers are assumed to impose a pressure loss of 0.05” wg. on the system.
xiv. The supply plenum within the furnace assembly is assumed to impose a head loss of 0.5” wg.
xv. To allow conservative design and due to the small duct sizes in this design, the designers assumed equivalent losses for ducts smaller than 6” are the same as losses for ducts that have 6” diameters.

To better quantify the duct design, the following figures were created to indicate the lengths and branch designations of the ducts in this system. Ducts that are part of the risers have the prefix “R”, ducts that are in the basement have the prefix “B”, the first and second floors are indicated by “F” and “S”, respectively. These drawings indicate lengths approximated from the architectural drawings, however the figures are NOT to scale, and proper drawings will have to be created to ensure this mechanical system is compatible with the current residence design.

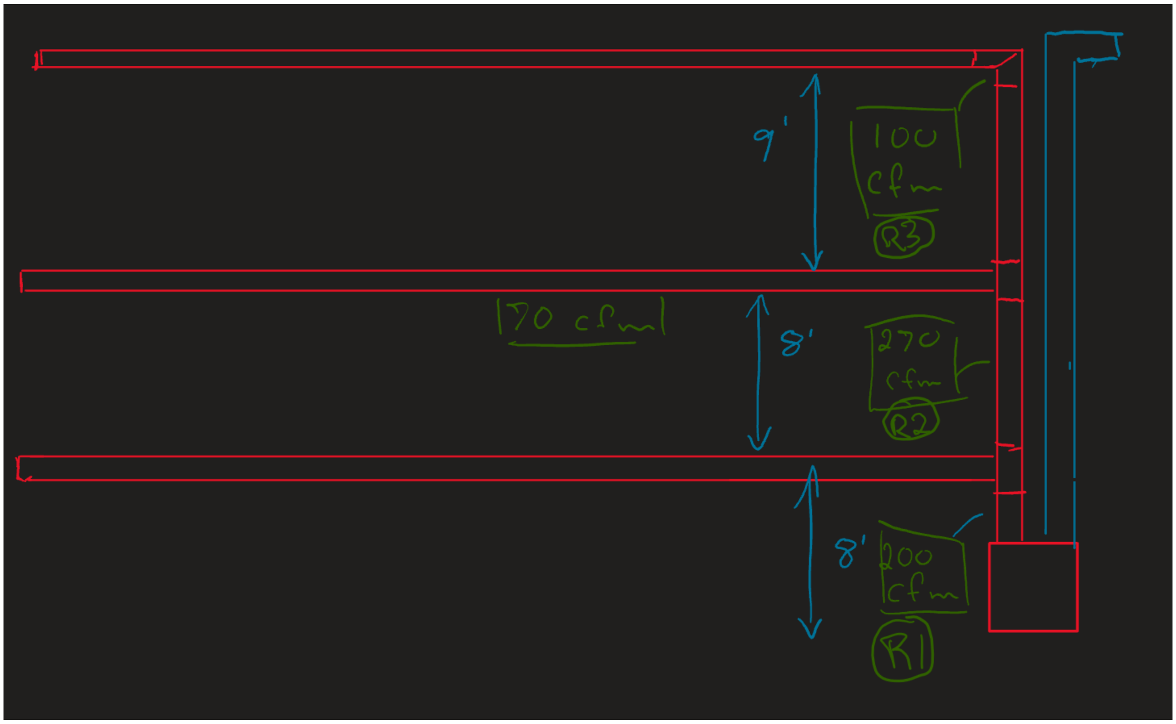


Figure 15: Riser elevation drawing indicating lengths and flow rates

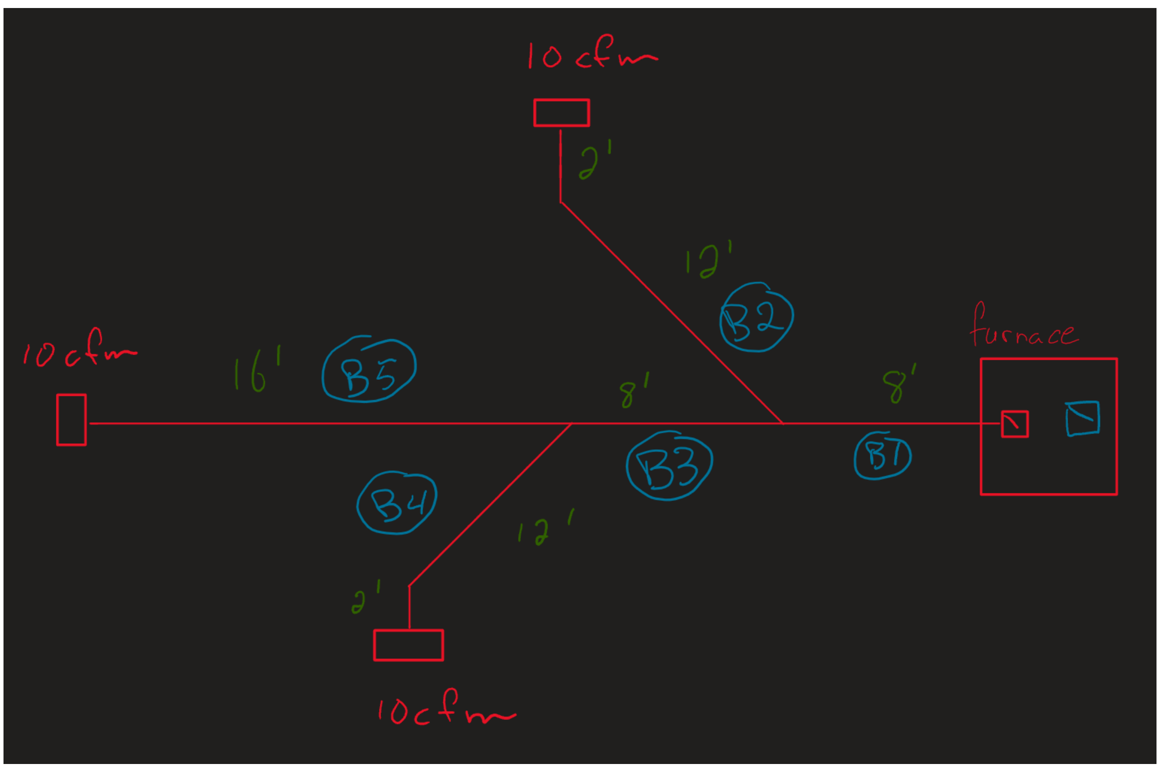


*Figure 16:*Basement mechanical layout indicating lengths, branches and flow rates

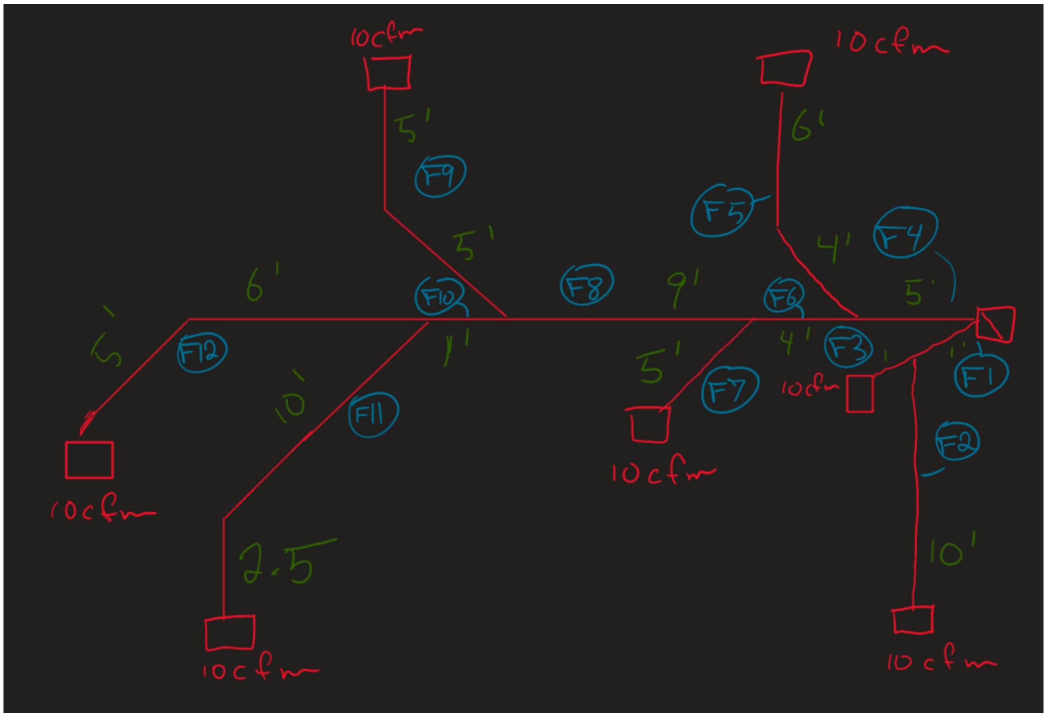


Figure 17: First floor mechanical layout indicating lengths, branches, and flow rates

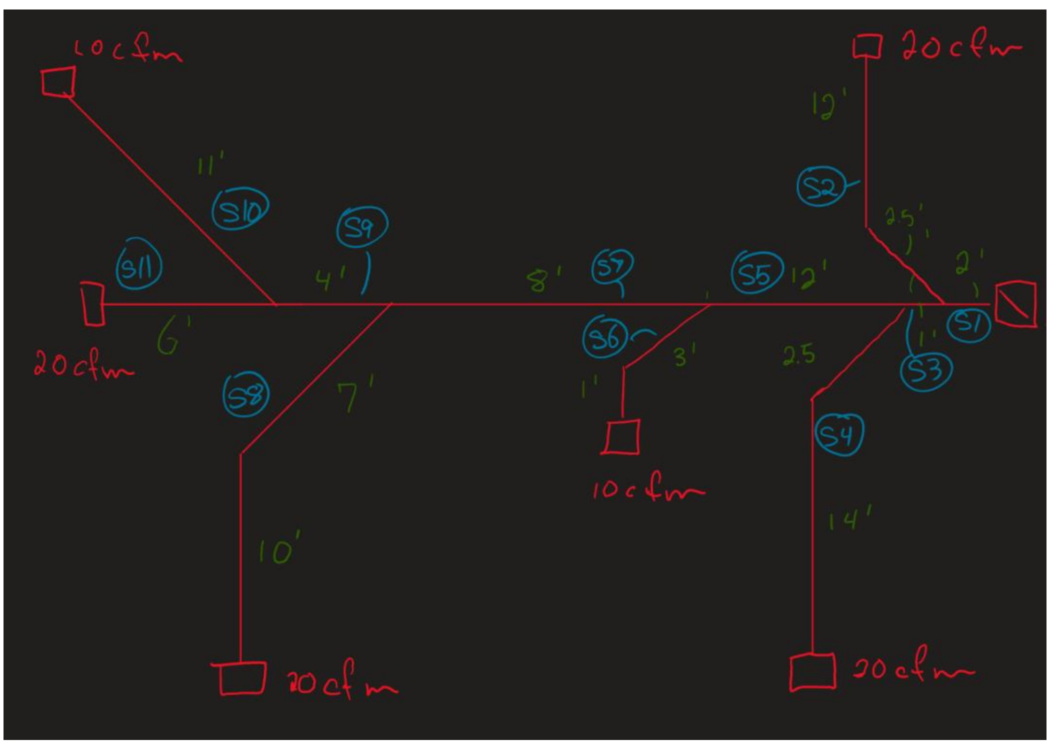


Figure 18: Second floor mechanical layout indicating lengths, branches, and flow rates

Determination of Ventilation Rates

When determining the heating losses due to infiltration and ventilation (Appendix A-3), ASHRAE Standard 62.2. was used, providing a minimum required ventilation rate of 127.92 cfm. To allow for conservative design, this value was increased to 200 cfm for the calculation of duct airflow (as well as to determine humidification requirements in Appendix C). This increase is in accordance with ASHRAE 61.2 and Table 5-9 in [1], shown below.

Table 14: Minimum Ventilation Rates in Breathing Zone for Dwelling Units taken from Table 5-9 in [1]

	People Outdoor Air Rate R_p		Area Outdoor Air Rate R_a			Default Values: Occupant Density (see Note 4)	Default Values: Combined Outdoor Air Rate (see Note 5)		
Occupancy Category	cfm/person	L/s·person	cfm/ft^2	L/s·m^2	Notes	#/1000 ft^2 or #/100 m^2	cfm/person	L/s·person	Air Class
Residential									
Dwelling unit	5	2.5	0.06	0.3	F,G, H	F			1
Common corridors			0.06	0.3	H				1

Using the values per unit area as well as per person, the following airflow is determined using the building floor area and occupancy:

$$Q = (3\text{ floors})(32\text{ ft})(34\text{ ft})\left(0.06\,\frac{\text{cfm}}{\text{ft}^2}\right) + \left(5\,\frac{\text{cfm}}{\text{person}}\right)(4\text{ people})$$

$$Q = 215.8\text{ cfm} \sim 200\text{ cfm}$$

As this value is larger than the ventilation requirement calculated in Appendix A-3, the designers selected it for use in the duct design as a more conservative estimate of airflow requirements.

Sizing of Ducts

Using the airflow determined above and the sections of ductwork shown in the figures above, the duct flow rates can be determined. The graphical method described by McDonald and Magande [8] was used to find the circular diameter for the ducts in this residential heating system. Using the assumed friction losses (0.1"wg per 100 ft.), the duct diameters were selected, providing more accurate values for air velocity and friction losses. The results of the graphical method are tabulated below.

Table 15: Table indicating the process of duct sizing and the final recommended duct sizes for each branch of the system.

Duct Sizing	Q	D	V	ΔP$_i$	L$_i$
Risers	**Air Flow Rate (cfm)**	**Diameter (in)**	**Velocity (fpm)**	**Friction Loss ("wg. per 100 ft)**	**Length (ft)**
R1	200	**8**	600	0.08	8
R3	170	**7**	600	0.11	8
R5	100	**6**	500	0.09	9
Basement					

B1	30	**4**	500	0.07	8
B2	10	**3**	500	0.07	14
B3	20	**4**	500	0.04	8
B4	10	**3**	500	0.07	14
B5	10	**3**	500	0.07	16
First Floor					
F1	20	**4**	500	0.04	1
F2	10	**3**	500	0.07	10
F3	10	**3**	500	0.07	1
F4	70	**5**	500	0.11	5
F5	10	**3**	500	0.07	10
F6	40	**4**	500	0.11	4
F7	10	**3**	500	0.07	5
F8	30	**4**	500	0.07	9
F9	10	**3**	500	0.07	10
F10	20	**4**	500	0.04	1
F11	10	**3**	500	0.07	12.5
F12	10	**3**	500	0.07	11
Second Floor					
S1	100	**6**	500	0.09	2
S2	20	**4**	500	0.04	14.5
S3	80	**5**	500	0.11	1
S4	20	**4**	500	0.04	16.5
S5	60	**5**	500	0.08	12
S6	10	**3**	500	0.07	4
S7	50	**5**	500	0.06	8
S8	20	**4**	500	0.04	17
S9	30	**4**	500	0.07	4
S10	10	**3**	500	0.07	11
S11	20	**4**	500	0.04	6

Due to the very small air flow rates within these ducts, no velocity approached 800 fpm or 1200 fpm, so there will be no issues regarding system noise. These small duct diameters also imposed very small duct friction losses. Once the separate duct sections were sized, they were organized into branches as shown below.

Table 16: Branches of the duct system

Branches	Total Length	
Basement		
R1-B1-B2	65	
R1-B1-B3-B4	77	
R1-B1-B3-B5	68	
First Floor		
R1-R3-F1-F2	91	
R1-R3-F1-F3	56	
R1-R3-F4-F5	74	
R1-R3-F4-F6-F7	72	
R1-R3-F4-F6-F8-F9	95	
R1-R3-F4-F6-F8-F10-F11	102.5	
R1-R3-F4-F6-F8-F10-F12	95	
Second Floor		
R1-R3-R5-S1-S2	69.5	
R1-R3-R5-S1-S3-S4	76.5	
R1-R3-R5-S1-S3-S5-S6	80	
R1-R3-R5-S1-S3-S5-S7-S8	**105**	**Longest Branch**
R1-R3-R5-S1-S3-S5-S7-S9-S10	102	
R1-R3-R5-S1-S3-S5-S7-S9-S11	91	

To determine the required pump head to supply sufficient airflow to the system, the longest branch was determined. If a blower can supply air to the longest branch in a system, then it can supply the whole system. Using the individual head losses of each section in the longest branch, this maximum head loss is determined. The summation equation is provided below with an example term.

$$\Delta P = \Delta P_{plenum} + \Delta P_{diffuser} + \sum_{1}^{N} \Delta P_i \, L_i = \Delta P_{plenum} + \Delta P_{diffuser} + \Delta P_{R1} L_{R1} + \cdots$$

$$= 0.5 \text{ in. wg} + 0.05 \text{ in. wg} + \left(\frac{0.08 \text{ in wg.}}{100 \text{ ft}}\right)(8 \text{ ft}) + \cdots$$

This equation was used to determine that the required head to supply adequate ventilation to this residence is 0.6166" wg. at 200 cfm using the ducts shown above.

APPENDIX E – ECONOMIC ANALYSIS OF HEATING SYSTEM

Table 17: Heating Values

Heating Degree-Days/Heating Values		
Component	**Value**	**Note**
HV (Natural gas, Btu/ft^3)	1050	Table 8-1
HV (Electricity, Btu/kWh)	3413	Table 8-1

Table 18: ECPOR service costs (taken from EPCOR energy bill on 11/01/2019)

Service	Rate
EPCOR Natural Gas	1.04 $/GJ
EPCOR Electricity	0.0634 $/kWh

The Bin Method energy use determination is included in the Tables below for the four different heat pumps possible for this system and for the furnace alone. After those tables, the life cycle analysis is included. To conserve space, the column headers are as follows:

A: Temperature Bin (°F)

B: Temperature Difference (°F)

C: Weather Data Bin (hours)

D: Total Latent Heat Load (Btu/h)

E: Heat Pump Integrated Heading Capacity (Btu/h)

F: Cycling Capacity Adjustment Factor

G: Adjusted Heat Pump Capacity (Btu/h)

H: Rated Electric Output (kW)

I: Operating Time Fraction

J: Heat Pump Supplied Heating (Btu)

K: Seasonal Heat Pump Electric Consumption (kWh)

L: Heat Pump Electricity Cost ($/yr)

M: Space Load (Btu)

N: Supplemental Furnace Heating Required (kWh)

O: Total Electric Consumption (kWh)

P: Natural Gas Consumption (ft^3)

Q: Natural Gas Cost ($/yr)

The following notes apply to the bin method tables (from [1]):

i. Cycling Capacity Adjustment Factor (Column F) is found with $1 - C_d(1 - x)$, where C_d is the degradation coefficient (Assumed to be 0.25), and x is the building heat loss per unit capacity
ii. Column G = Column E x Column F
iii. Operating Time Fraction is the smaller value between (Column D/Column G) or 1.00.
iv. Column J = (Column I x Column G x Column C)/1000
v. Column K = Column I x Column H x Column C
vi. Column L = Column C x Column D/1000
vii. Column M = (Column L – Column J) x 10^6/3413
viii. Column N = Column K + Column M

Heat Pump Energy Consumption - A030 (Ch.8, pg.313)

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
72	-2	417	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
67	3	463	13649.61	41800	0.8316364234	34762.4025	3.35	0.3926543915	6319769.43	609.0265939	$38.61	6319769.43	0	609.0265939	0	$0.00
62	8	521	16250.29	39400	0.8531109772	33612.5725	3.25	0.483458682	8466401.09	818.6164133	$51.90	8466401.09	0	818.6164133	0	$0.00
57	13	803	18850.98	37000	0.8773714865	32462.745	3.14	0.5806958099	15137336.94	1464.178029	$92.83	15137336.94	0	1464.178029	0	$0.00
52	18	844	21451.66	34500	0.9054468116	31237.915	3.02	0.6867186879	18105201.04	1750.363529	$110.97	18105201.04	0	1750.363529	0	$0.00
47	23	612	24052.35	31800	0.9390908019	29863.0875	2.89	0.8054207389	14720038.2	1424.531552	$90.32	14720038.2	0	1424.531552	0	$0.00
42	28	684	26653.03	29600	0.9751100507	28863.2575	2.8	0.9234241838	18230672.52	1768.541997	$112.13	18230672.52	0	1768.541997	0	$0.00
37	33	733	29253.71	27300	1	27300	2.69	1	20010900	1971.77	$125.01	21442969.43	419.5925667	2391.362567	1363.875648	$1.57
32	38	675	31854.4	24900	1	24900	2.57	1	16807500	1734.75	$109.98	21501720	1375.394081	3110.144081	4470.685714	$5.15
27	43	697	34455.08	22700	1	22700	2.47	1	15821900	1721.59	$109.15	24015190.76	2400.612587	4122.202587	7803.134057	$8.99
22	48	468	37055.77	20500	1	20500	2.36	1	9594000	1104.48	$70.02	17342100.36	2270.172974	3374.652974	7379.1432	$8.50
17	53	453	39656.45	18600	1	18600	2.26	1	8425800	1023.78	$64.91	17964371.85	2794.776399	3818.556399	9084.354143	$10.47
12	58	307	42257.14	16600	1	16600	2.17	1	5096200	666.19	$42.24	12972941.98	2307.864629	2974.054629	7501.659029	$8.64
7	63	311	44857.82	14800	1	14800	2.09	1	4602800	649.99	$41.21	13950782.02	2738.934081	3388.924081	8902.840019	$10.26
2	68	230	47458.51	13200	1	13200	2.01	1	3036000	462.3	$29.31	10915457.3	2308.660211	2770.960211	7504.245048	$8.65
-3	73	197	50059.19	11800	1	11800	1.94	1	2324600	382.18	$24.23	9861660.43	2208.338831	2590.518831	7178.15279	$8.27
-8	78	154	52659.88	10600	1	10600	1.88	1	1632400	289.52	$18.36	8109621.52	1897.808825	2187.328825	6168.7824	$7.11
-13	83	91	55260.56	9700	1	9700	1.83	1	882700	166.53	$10.56	5028710.96	1214.770278	1381.300278	3948.581867	$4.55
-18	88	56	57861.25	8900	1	8900	1.8	1	498400	100.8	$6.39	3240230	803.3489599	904.1489599	2611.266667	$3.01
-25	95	34	61502.2	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	2091074.8	612.6794023	612.6794023	1991.49981	$2.29
-35	105	10	66703.57	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	667035.7	195.4397011	195.4397011	635.2720952	$0.73
								Totals	169712619.2	18109.13811	**$1,148.12**	250083286.3	23548.39353	41657.53164	76543.49249	**$88.19**
															Total Cost	**$1,236.31**

Heat Pump Energy Consumption - A036 (Ch.8, pg.313)																
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
72	-2	417	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
67	3	463	13649.61	51200	0.8166484863	41812.4025	4.19	0.326448833	6319769.43	633.3009425	$40.15	6319769.43	0	633.3009425	0	$0.00
62	8	521	16250.29	48300	0.8341112319	40287.5725	4.05	0.4033573877	8466401.09	851.1042559	$53.96	8466401.09	0	851.1042559	0	$0.00
57	13	803	18850.98	45200	0.8542642699	38612.745	3.91	0.4882061609	15137336.94	1532.83553	$97.18	15137336.94	0	1532.83553	0	$0.00
52	18	844	21451.66	42200	0.8770832938	37012.915	3.77	0.5795722925	18105201.04	1844.129486	$116.92	18105201.04	0	1844.129486	0	$0.00
47	23	612	24052.35	39000	0.9041817308	35263.0875	3.61	0.6820829288	14720038.2	1506.939456	$95.54	14720038.2	0	1506.939456	0	$0.00
42	28	684	26653.03	36100	0.9345777701	33738.2575	3.48	0.7899942669	18230672.52	1880.439153	$119.22	18230672.52	0	1880.439153	0	$0.00
37	33	733	29253.71	33100	0.9709494713	32138.4275	3.33	0.9102408635	21442969.43	2221.797821	$140.86	21442969.43	0	2221.797821	0	$0.00
32	38	675	31854.4	30100	1	30100	3.19	1	20317500	2153.25	$136.52	21501720	346.9733372	2500.223337	1127.828571	$1.30
27	43	697	34455.08	27300	1	27300	3.05	1	19028100	2125.85	$134.78	24015190.76	1461.204442	3587.054442	4749.610248	$5.47
22	48	468	37055.77	24500	1	24500	2.91	1	11466000	1361.88	$86.34	17342100.36	1721.68191	3083.56191	5596.286057	$6.45
17	53	453	39656.45	22000	1	22000	2.76	1	9966000	1250.28	$79.27	17964371.85	2343.501861	3593.781861	7617.497	$8.78
12	58	307	42257.14	19500	1	19500	2.65	1	5986500	813.55	$51.58	12972941.98	2047.009077	2860.559077	6653.754267	$7.67
7	63	311	44857.82	17200	1	17200	2.55	1	5349200	793.05	$50.28	13950782.02	2520.24085	3313.29085	8191.982876	$9.44
2	68	230	47458.51	15100	1	15100	2.44	1	3473000	561.2	$35.58	10915457.3	2180.620363	2741.820363	7088.054571	$8.17
-3	73	197	50059.19	13300	1	13300	2.35	1	2620100	462.95	$29.35	9861660.43	2121.75811	2584.70811	6896.724219	$7.95
-8	78	154	52659.88	11700	1	11700	2.27	1	1801800	349.58	$22.16	8109621.52	1848.175072	2197.755072	6007.449067	$6.92
-13	83	91	55260.56	10300	1	10300	2.21	1	937300	201.11	$12.75	5028710.96	1198.772622	1399.882622	3896.581867	$4.49
-18	88	56	57861.25	9300	1	9300	2.15	1	520800	120.4	$7.63	3240230	796.7858189	917.1858189	2589.933333	$2.98
-25	95	34	61502.2	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	2091074.8	612.6794023	612.6794023	1991.49981	$2.29
-35	105	10	66703.57	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	667035.7	195.4397011	195.4397011	635.2720952	$0.73
								Totals	183888688.7	20663.64665	**$1,310.08**	250083286.3	19394.84257	40058.48921	63042.47398	**$72.63**
															Total Cost	**$1,382.71**

Heat Pump Energy Consumption - A048 (Ch.8, pg.313)

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
72	-2	417	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
67	3	463	13649.61	66700	0.8011604573	53437.4025	5.33	0.2554317643	6319769.43	630.3519536	$39.96	6319769.43	0	630.3519536	0	$0.00
62	8	521	16250.29	63000	0.8144852778	51312.5725	5.16	0.3166921713	8466401.09	851.3825656	$53.98	8466401.09	0	851.3825656	0	$0.00
57	13	803	18850.98	59200	0.8296071791	49112.745	4.99	0.3838307144	15137336.94	1537.998158	$97.51	15137336.94	0	1537.998158	0	$0.00
52	18	844	21451.66	55400	0.8468035199	46912.915	4.81	0.4572655526	18105201.04	1856.333528	$117.69	18105201.04	0	1856.333528	0	$0.00
47	23	612	24052.35	51000	0.8679036765	44263.0875	4.6	0.5433952162	14720038.2	1529.766213	$96.99	14720038.2	0	1529.766213	0	$0.00
42	28	684	26653.03	48000	0.8888178646	42663.2575	4.46	0.624730308	18230672.52	1905.827267	$120.83	18230672.52	0	1905.827267	0	$0.00
37	33	733	29253.71	44400	0.9147168356	40613.4275	4.28	0.7202965078	21442969.43	2259.743016	$143.27	21442969.43	0	2259.743016	0	$0.00
32	38	675	31854.4	40800	0.9451862745	38563.6	4.1	0.8260224668	21501720	2286.017177	$144.93	21501720	0	2286.017177	0	$0.00
27	43	697	34455.08	37300	0.9809321716	36588.77	3.93	0.9416845661	24015190.76	2579.47178	$163.54	24015190.76	0	2579.47178	0	$0.00
22	48	468	37055.77	33800	1	33800	3.78	1	15818400	1769.04	$112.16	17342100.36	446.4401875	2215.480188	1451.1432	$1.67
17	53	453	39656.45	30000	1	30000	3.58	1	13590000	1621.74	$102.82	17964371.85	1281.679417	2903.419417	4166.068429	$4.80
12	58	307	42257.14	27300	1	27300	3.45	1	8381100	1059.15	$67.15	12972941.98	1345.397592	2404.547592	4373.182838	$5.04
7	63	311	44857.82	24200	1	24200	3.31	1	7526200	1029.41	$65.26	13950782.02	1882.38559	2911.79559	6118.649543	$7.05
2	68	230	47458.51	21200	1	21200	3.18	1	4876000	731.4	$46.37	10915457.3	1769.545063	2500.945063	5751.864095	$6.63
-3	73	197	50059.19	18400	1	18400	3.06	1	3624800	602.82	$38.22	9861660.43	1827.38366	2430.20366	5939.867076	$6.84
-8	78	154	52659.88	15700	1	15700	2.95	1	2417800	454.3	$28.80	8109621.52	1667.688696	2121.988696	5420.7824	$6.25
-13	83	91	55260.56	13200	1	13200	2.86	1	1201200	260.26	$16.50	5028710.96	1121.450618	1381.710618	3645.248533	$4.20
-18	88	56	57861.25	10900	1	10900	2.78	1	610400	155.68	$9.87	3240230	770.5332552	926.2132552	2504.6	$2.89
-25	95	34	61502.2	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	2091074.8	612.6794023	612.6794023	1991.49981	$2.29
-35	105	10	66703.57	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	667035.7	195.4397011	195.4397011	635.2720952	$0.73
								Totals	205985199.4	23120.69166	**$1,465.85**	250083286.3	12920.62318	36041.31484	41998.17802	**$48.39**
															Total Cost	**$1,514.24**

Heat Pump Energy Consumption - A060 (Ch.8, pg.313)																
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
72	-2	417	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
67	3	463	13649.61	86200	0.789587036	68062.4025	7.02	0.2005455214	6319769.43	651.8250865	$41.33	6319769.43	0	651.8250865	0	$0.00
62	8	521	16250.29	81300	0.7999701415	65037.5725	6.79	0.2498600328	8466401.09	883.9023535	$56.04	8466401.09	0	883.9023535	0	$0.00
57	13	803	18850.98	76300	0.8117659895	61937.745	6.56	0.30435367	15137336.94	1603.23774	$101.65	15137336.94	0	1603.23774	0	$0.00
52	18	844	21451.66	71200	0.8253218399	58762.915	6.32	0.3650543885	18105201.04	1947.229312	$123.45	18105201.04	0	1947.229312	0	$0.00
47	23	612	24052.35	66000	0.8411073864	55513.0875	6.05	0.4332735051	14720038.2	1604.23848	$101.71	14720038.2	0	1604.23848	0	$0.00
42	28	684	26653.03	61000	0.8592337295	52413.2575	5.81	0.508516953	18230672.52	2020.866712	$128.12	18230672.52	0	2020.866712	0	$0.00
37	33	733	29253.71	56000	0.8805969196	49313.4275	5.56	0.5932199704	21442969.43	2417.656125	$153.28	21442969.43	0	2417.656125	0	$0.00
32	38	675	31854.4	51000	0.9061490196	46213.6	5.3	0.6892862707	21501720	2465.921633	$156.34	21501720	0	2465.921633	0	$0.00
27	43	697	34455.08	46300	0.9360425486	43338.77	5.05	0.7950174867	24015190.76	2798.3423	$177.41	24015190.76	0	2798.3423	0	$0.00
22	48	468	37055.77	41700	0.9721568945	40538.9425	4.81	0.9140783581	17342100.36	2057.66351	$130.46	17342100.36	0	2057.66351	0	$0.00
17	53	453	39656.45	3700	1	3700	4.61	1	1676100	2088.33	$132.40	17964371.85	4772.4207	6860.7507	15512.63986	$17.87
12	58	307	42257.14	33200	1	33200	4.35	1	10192400	1335.45	$84.67	12972941.98	814.6914679	2150.141468	2648.135219	$3.05
7	63	311	44857.82	29400	1	29400	4.13	1	9143400	1284.43	$81.43	13950782.02	1408.550255	2692.980255	4578.459067	$5.27
2	68	230	47458.51	26000	1	26000	3.94	1	5980000	906.2	$57.45	10915457.3	1446.075974	2352.275974	4700.435524	$5.42
-3	73	197	50059.19	23000	1	23000	3.76	1	4531000	740.72	$46.96	9861660.43	1561.869449	2302.589449	5076.819457	$5.85
-8	78	154	52659.88	20400	1	20400	3.6	1	3141600	554.4	$35.15	8109621.52	1455.617205	2010.017205	4731.449067	$5.45
-13	83	91	55260.56	18300	1	18300	3.47	1	1665300	315.77	$20.02	5028710.96	985.470542	1301.240542	3203.248533	$3.69
-18	88	56	57861.25	16800	1	16800	3.36	1	940800	188.16	$11.93	3240230	673.7269265	861.8869265	2189.933333	$2.52
-25	95	34	61502.2	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	2091074.8	612.6794023	612.6794023	1991.49981	$2.29
-35	105	10	66703.57	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	667035.7	195.4397011	195.4397011	635.2720952	$0.73
								Totals	202551999.8	25864.34325	**$1,639.80**	250083286.3	13926.54162	39790.88488	45267.89196	**$52.15**
															Total Cost	**$1,691.95**

Natural Gas Furnace Only (No Heat Pump)																
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
72	-2	417	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
67	3	463	13649.61	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	6319769.43	1851.675778	1851.675778	6018.828029	$6.93
62	8	521	16250.29	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	8466401.09	2480.633194	2480.633194	8063.239133	$9.29
57	13	803	18850.98	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	15137336.94	4435.199807	4435.199807	14416.51137	$16.61
52	18	844	21451.66	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	18105201.04	5304.776162	5304.776162	17243.04861	$19.87
47	23	612	24052.35	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	14720038.2	4312.932376	4312.932376	14019.084	$16.15
42	28	684	26653.03	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	18230672.52	5341.538975	5341.538975	17362.54526	$20.00
37	33	733	29253.71	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	21442969.43	6282.733498	6282.733498	20421.87565	$23.53
32	38	675	31854.4	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	21501720	6299.94726	6299.94726	20477.82857	$23.59
27	43	697	34455.08	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	24015190.76	7036.387565	7036.387565	22871.61025	$26.35
22	48	468	37055.77	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	17342100.36	5081.189675	5081.189675	16516.28606	$19.03
17	53	453	39656.45	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	17964371.85	5263.51358	5263.51358	17108.92557	$19.71
12	58	307	42257.14	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	12972941.98	3801.037791	3801.037791	12355.18284	$14.23
7	63	311	44857.82	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	13950782.02	4087.542344	4087.542344	13286.45907	$15.31
2	68	230	47458.51	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	10915457.3	3198.200205	3198.200205	10395.67362	$11.98
-3	73	197	50059.19	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	9861660.43	2889.440501	2889.440501	9392.057552	$10.82
-8	78	154	52659.88	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	8109621.52	2376.09772	2376.09772	7723.449067	$8.90
-13	83	91	55260.56	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	5028710.96	1473.399051	1473.399051	4789.248533	$5.52
-18	88	56	57861.25	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	3240230	949.3788456	949.3788456	3085.933333	$3.56
-25	95	34	61502.2	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	2091074.8	612.6794023	612.6794023	1991.49981	$2.29
-35	105	10	66703.57	N/A	N/A	N/A	N/A	N/A	0	0	$0.00	667035.7	195.4397011	195.4397011	635.2720952	$0.73
								Totals	0	0	**$0.00**	250083286.3	73273.74343	73273.74343	238174.5584	**$274.41**
															Total Cost	**$274.41**

Year	0	1	2	3	4	5	6	7	8	9	10
First cost($)	4630										
Energy cost($)	0	274.41	279.89	285.5	291.2	297.03	302.97	309.03	315.21	321.52	327.95
Maintanace cost($)	0	0	0	150	0	0	180	0	0	216	0
Annual net cash flow($)	4630	274.41	279.89	435.5	291.2	297.03	482.97	309.03	315.21	537.52	327.95
										Lifecycle cost($)	8180.71

Year	0	1	2	3	4	5	6	7	8	9	10
First cost($)	6278										
Energy cost($)	0	1236.45	1261.17	1286.4	1312.13	1338.37	1365.14	1392.44	1420.29	1448.69	1477.67
Maintanance cost($)	0	0	0	150	0	0	180	0	0	216	0
Annual net cash flow($)	6278	1236.45	1261.17	1436.4	1312.13	1338.37	1545.14	1392.44	1420.29	1664.69	1477.67
										Lifecycle cost($)	20362.75