Air to Water Heat Pump Demonstration

Final Report

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Notice

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Acronyms and Abbreviations

Air-to-Air HP	Air-to-Air Heat Pump
Air-to-Water HP	Air-to-Water Heat Pump
Btu	British Thermal Unit
kBtu	Thousand British Thermal Units
C	Degrees Celsius
CFM	Cubic Feet Per Minute (air flow rate)
F	Degrees Fahrenheit
ft	feet, also noted as ‘
GPM	Gallons Per Minute (water/fluid flow rate)
HP	Heat Pump
HVAC	Heating Ventilation and Air Conditioning
Hx	Heat Exchanger
kW	kilowatt
kWh	kilowatt hours
m/s	meters per second
MW	megawatts
NYS	New York State
NYSERDA	New York State Energy Research and Development Authority
OAT	Outdoor Air Temperature
RWT	Return Water Temperature
SWT	Supply Water Temperature
W	Watts

Executive Summary

This demonstration project confirmed the potential for the use of air-to-water heat pump technology in residential buildings in New York State. Although the technology is commercially available, it is still new, and in many cases, more expensive than other options. It is most likely to appeal primarily to customers who identify as early-adopters and whose homes have radiant floor distribution with a source of backup heating. There was increased interest and awareness of the technology over the course of this demonstration project, with multiple inquiries from homeowners about installation in new construction projects.

As part of this demonstration project, five air-to-water heat pumps were installed at sites in New York. The Solstice Extreme heat pump was installed at four of the sites, whereas a Sanden SanCO2 heat pump was installed at the fifth. All five sites made it through the winter.

Table 1: Air-to-water heat pump demonstration sites

Air-to-water heat pumps installed at the different sites involved in this demonstration project.

Site	Heating System Selected	Location Details
Sapsucker Woods Road	Solstice Extreme	Four-unit apartment building. Ithaca, NY
Firetower Road	Sanden SanCO2	Single family residence. Caroline, NY
Riders Mills Road	Solstice Extreme	Single family residence. Old-Chatham, NY
Steuben Valley Road	Solstice Extreme	Residential Home-office outbuilding. Holland Patent, NY
Garrett Road	Solstice Extreme	Single family residence. Ulysses, NY

The technology struggles to provide a cost-effective alternative to air-to-air heat pumps or natural gas fired heating systems. Installation at sites without natural gas and with either an existing hydronic heating system serving many small rooms or new construction buildings with radiant floor heat are likely to yield the best results. New construction allows the distribution system to be designed to operate within the flow and temperature limitations required by these heat pumps. There are potential issues when installing an air-to-water heat pump as a retrofit in an existing high-temperature distribution system. Implementation at sites with a high density of small heating zones is one scenario in which an air-to-water heat pump system was more cost effective than a similar air-to-air heat pump system.

1 Introduction

In partnership with NYSERDA, Taitem Engineering completed a demonstration project focused on the practical application of air-to-water heat pumps for heating use in residential style buildings. Throughout the project phases, Taitem identified market barriers to broader adoption of air-to-water heat pumps. Design strategies were developed to circumvent some of the barriers to adoption for this technology, although barriers related to cost and installation contractors remain.

1.1 Background and Project Objectives

The objective of this demonstration project was to validate the use of air-to-water heat pumps in existing residential building retrofits by using a comprehensive design and analysis process. The project addresses real and perceived barriers to widespread adoption of air-to-water heat pumps. For example, low supply water temperatures are a barrier to air-to-water heat pumps that can be addressed with design protocols. Equipment costs are another concern, which can be addressed with suitable site selection. A comprehensive list outlining the barriers identified and assessed by this project is included in Section 1.1.1, Barriers to Adoption.

The main phases of this project were 1) site selection, 2) retrofit planning, and 3) retrofit execution. A collaboration with HeatSmart Tompkins was helpful in identifying interested homeowners. HeatSmart Tompkins spoke about the project during their outreach meetings, and they provided a link on their website for homeowners to sign up to be considered. Over 50 homeowners were engaged and screened for site suitability. There were eight in-depth site visits for preliminary assessment and design. These homeowners received an assessment to determine the specific scope of work unique to each house, combined with a heat load calculation and a cost estimate. Taitem provided schematic design for each of the air-to-water heat pump installations, including heat loss calculations, sizing of the heat pump, any necessary modifications to the distribution system, and controls specifications. Each of the final sites selected for the project featured a workable design and a strong homeowner commitment. Sites were vetted by NYSERDA and NYSERDA's measurement and verification (M&V) contractor, Frontier Energy.

The retrofit planning phase required working with the homeowners and moving from schematic design to design development. The heat pump, heat exchanger, buffer tank, expansion tank, and balance of system components were specified for each installation, typically after considering multiple options. M&V contractor Frontier Energy was informed of the designs and kept in the loop as the designs evolved.

The proposed plan for the retrofit execution phase was to work with a local heating and plumbing contractor for the installations. Due to the nature of the demonstration, with a new technology and new controls integration between the heat pump and the existing boiler, Taitem was unable to identify a local contractor. Taitem completed three of the installations with an in-house hydronics engineer. Two of the installations were installed by homeowners who are professionals in the hydronics field. Taitem coordinated with Frontier Energy to assist with inspections, installation of instrumentation, data collection, and troubleshooting.

1.1.1 Barriers to Adoption

The following barriers to adoption were noted and explored over the course of this demonstration project:

- Homeowner resistance to new technology (Expected, not encountered because project attracted early adopters)
- Inadequate water temperature provided by the heat pump (Limiting, often surmountable but increases the scope of installation)
- Inadequate heating capacity (Limiting, surmountable when heat pump used as supplement instead of replacement to existing heating system)
- Limited availability of heat pump systems (Limiting, market offerings are evolving, only a few well-developed products available)
- Lack of installer familiarity or interest in the technology (Encountered, a major impediment)
- Difficulty integrating system with existing distribution and heating systems (Encountered, surmountable but increases design effort)
- Lack of suitable packaged control systems (Expected, surmountable, several suitable controllers available)
- Lack of control setup and setpoint guidance (Encountered, not expected and limiting to optimal operation)
- Lack of adequate installation documentation and support (Encountered, not expected and limiting to broader adoption and installer trust of technology)
- High equipment hard-costs (Encountered, more limiting than expected for most installations, cost competitive in one instance)
- High installation (labor) costs (Encountered, more limiting than expected)
- Relative fuel costs (Encountered, more limiting than expected, only a viable cost-effective option for electric, oil or propane)
- High level of customization and design needed for each project (Encountered, more limiting than expected, some simplifications possible but no one-size-fits-all solution)
- Lack of maintenance and service contractors (Anticipated limitation)
- Reliability of equipment (Encountered)

1.1.2 Common aspects of successful air-to-water demonstration projects

Over the course of this demonstration project, we discovered that whereas each project varied greatly in the details, the implementation strategy that was eventually pursued, and generally most cost effective, followed a similar approach. With a few exceptions, the approach for each of the implemented projects consisted of the following:

1. Air-to-water heat pumps were used to supplement, instead of replace, existing systems with as few modifications to distribution elements within living spaces as possible.
    - Existing hot water boilers were retained with full functionality for backup use and to take over during colder outdoor air periods
    - Existing hydronic distribution systems were kept largely as-is, even when not designed as low temperature systems, to allow the backup system to operate when needed
    - Installations were limited in scope, with work located primarily in basements or mechanical closets.
2. The demonstration sites varied broadly in their loads and existing hydronic infrastructure. Despite that variability, the same make, model and size heat pump was chosen at all but one of the sites. A thorough review of available air-to-water heat pumps was performed, and an alternate heat pump was provided as part of the design analysis.
    - The most frequently selected unit was one with the highest market penetration in North America, and it achieved a balance between capacity, output temperature, price point and reliability/reputation.

1.1.3 Evaluated, but not implemented approaches

Several design strategies were evaluated and proposed at the site selection and design development stages of the demonstration project. For various reasons, these alternate approaches failed to lead to implementable projects, and as such, they are not a focus of this report. Some of these approaches may be suitable for other sites, or as lessons learned:

- Replacing failing older boiler systems with air-to-water heat pumps was evaluated at several sites; however, a backup system, either boiler, electric space heaters or otherwise, proved to still be needed, and the installation of two new systems required by this approach was cost prohibitive.
- A combination of more extensive alterations and supplements to heat distribution elements within living spaces, which would allow more effective use of the low supply water temperature from an air-to-water heat pump, was evaluated. With the other requirements for these systems, such as needing a form of backup heat, this approach was not cost effective.

    - Living rooms in particular tended to be challenging to serve with lower temperature water. A typical living room will have a single exterior wall with large windows, but contain, or be adjacent to, the main house entrance and open stairs that lead to upper floors. Living rooms typically have little radiation, but see loads from multiple adjacent spaces, such as the upstairs. They are a public facing space, and many homeowners are reluctant to install

additional or larger heating elements, limiting how much heat can be delivered to one of the most central and important spaces in the house.
    - Adding forced air elements such as convection heaters or fan coils, primarily to increase output capacity in rooms with limited space available to add radiation elements, proved to be a less cost effective and more disruptive alternative to installing one or more air-to-air heat pumps and eliminating the hydronic system in that space entirely.
- Improving the building envelope and implementing other load reduction strategies was not a viable option for most of the sites. Homeowners who were seriously interested in pursuing this technology had already implemented the most cost effective load reduction improvements.

1.2 Demonstration Equipment

1.2.1 Key System Components

1.2.1.1 Air-to-Water Heat Pump

All but one of the demonstration sites selected and installed a Solstice Extreme air-to-water heat pump. The remaining site installed a Sanden SanCO2 air-to-water heat pump. Although only two different models were ultimately installed, a thorough product search was conducted in the early stages of the project. Performance, cost, and reliability data were collected and vetted for thirteen other models. Several of the alternate units, presented later in the report in Section 1.2.3, Evaluated, but not used, Air-to-Water Heat Pumps were offered as design options to prospective sites.

1.2.1.1.1 Solstice Extreme

The primary advantages of the Solstice Extreme at the time of heat pump comparison were: its low-ambient capacity, which was greater than many competitors; relatively hot maximum supply water temperature of 140F; and relatively large number of past installations, which indicated the unit was meeting a minimum threshold of reliability and longevity. These factors were not the only ones considered when selecting a unit, but they are significant when considering which unit is most suitable for installation as a replacement for an existing heating system.

Out of all the air-to-water heat pumps considered, the Solstice Extreme unit was the most well-developed system and had an operating range that was the most compatible with an existing hydronic heating system. However, even the Solstice is not a mature product in comparison to non-air-to-water heat pump systems it is competing with and may not be ready for installation in many homes.

One encouraging sign is the recent release of a technical application manual for the Solstice Extreme unit. This was released in late 2018 and prepared in a partnership between John Siegenthaler, PE and Solstice. This manual will hopefully increase installer confidence and comfort level with installing these systems.

Figure 1: Solstice Extreme

Product image and listing of standard features for the unit from the manufacturer's submittal documentation

SUBMITTAL DATA: Heat Pump LAHP48 Series

SD-LAA6-1016

Low Ambient Air to Water Reverse Cycle Heat Pump

STANDARD FEATURES

- Hermetically Sealed EVI Compressor
- Self-Diagnostic Control – Factory Programmed Two Variable Speed Fans
- Brazed-plate Refrigerant-to-Water Heat Ex.
- Quiet Operation – 62dB
- R410A Refrigerant
- 208-230/1/60
- Durable Powder Coated Finish
- 64,680 BTU/hr at 47°F Ambient
- Configurable Defrost Logic
- Optimized for Buffer Tank Installation

Figure 2: Solstice Extreme Performance Metrics

Performance tables and data for the heat pump in heating and cooling at different ambient temperatures

Performance

LAHP Heating Operation at 120°F Water

Ambient Temp	Capacity BTU/hr	Electrical Power Watts	Heat Pump COP	Heat Pump EER
47°F	64,680	5,963	3.2	8.31
5°F	39,240	5,773	2.6	11.09

LAHP Cooling Operation at 44°F Water

Ambient Temp	Capacity BTU/hr	Electrical Power Watts	Heat Pump COP	Heat Pump EER
95°F	40,000	4,790	1.9	8.31
82°F	42,500	4,341	2.3	9.79

Specifications

Model	LAHP - 048	COP
Heating Capacity (47°F Ambient, 120°F Supply Water)	64,680 BTUh (18.9 kW)	3.18
Heating Capacity (17°F Ambient, 120°F Supply Water)	46,440 BTUh (13.6 kW)	2.35
Heating Capacity (5°F Ambient, 120°F Supply Water)	39,240 BTUh (11.5 kW)	2.35
Cooling Capacity (95°F Ambient, 44°F Supply Water)	40,000 BTUh (11.7 kW)	2.43
Voltage	230V/1ph/60Hz	
Min Supply Temp	42°F (5.5°C)	
Max Supply Temp	125°F (52°C)	
Min Water Flow	10 GPM (37.8 l/min)	
Nominal Water Flow	12 GPM (45.4 l/min)	
dP@ Max Flow	17.2 ft (35.8 kPa)	
Heating Current	31 Amps	
Cooling Current	23.5 Amps	
Noise Level	62 dB (A)	
Compressor	Scroll	
Installed Weight	386 lbs (175 Kg)	

1.2.1.1.2 Sanden SanCO2

The Sanden unit was desirable for some sites because of its low cost, high maximum supply temperature (170F) and unique refrigerant system using Carbon Dioxide (CO_2). The Sanden unit was first developed as a domestic hot water heater, and its use for heating is a relatively new application for Sanden. There are several features which work well in a domestic hot water heating system that currently do not translate well to heating. It is the only unit that we found that can produce supply water at temperatures approaching a traditional boiler system, which could greatly simplify integration with existing hydronic systems, assuming the other limitations can be overcome.

Figure 3: Sanden SanCO2

Product image of the Sanden heat pump, taken from the manufacturer's product documentation

Figure 4: Sanden Specification Metrics

Specification details for the Sanden Buffer Tank and Heat Pump

Outdoor Unit

Heat pump unit GUS-A45HPA

Refrigerant type	R744(CO_2)
Product weight	125lbs/57 kg
Thermal capacity	15,350 Btu/h 4.5 kw *1
Power consumption	1.0 kw *1
COP	4.5 *1
Heated water temp.	149 °F (65 °C)

*1 Ambient temp. (Dry / Wet) 61°F (16°C) / 63 °F (17°C), Inlet water temps. 63°F (17°C), Outlet water temp. 149°F (65°C)

Buffer Tank

Model No:		GAUS-315EQTB
A	Height	1540mm
F	Diameter	690mm

Storage capacity	83 / 66 gallons
Product weight	154 / 134 lbs
Design pressure	100 PSI (700 kPa)
Storage tank material	Stainless steel
Outside casing	Colour coated zinc steel

The Sanden unit is limited by several factors, which include: a very low capacity (8 kBtu or less if used for heating); a low maximum flow rate of roughly 0.5 GPM, which limits how quickly the heat can be delivered; a return water temperature limitation which prevents operation above 122F return water; the required installation of a specific and expensive Taco X-Block Heat Exchanger; the requirement that it be installed as a combination heating and domestic hot water system with a minimum of 25 gallons of domestic hot water use per day if used for heat; and the required installation of electric heat trace for freeze protection on all exterior pipes, unlike the other units which use a glycol mix in outdoor components.

Figure 5: Sanden Operating Limitations

Screenshot of manufacturer's presentation

DHW & Heating Combination

- Only use with HEAT LOADS < 8,000 Btu/h to ensure adequate cycle times on the Heat Pump
- Only use in climates with a design winter temperature (minimum expected coldest winter temperature of > 27°F
- DHW use is very important to maximize the energy in the tank, Minimum of 25 Gallons of DHW use is required daily
- Follow piping diagram – Use Potable / Non Potable separation and standard installation

SANCO2 GEN3

Despite these limitations, one of our five sites elected to pursue the Sanden unit, and the homeowner has been using it to serve a low temperature radiant floor slab, retaining the old electric boilers as backup.

While the use of the Sanden for space heating applications is a recent development and it is still clearly an emerging technology, the Sanden product is better developed than might be expected based on number of installations alone due to its genesis as a domestic hot water heater.

1.2.1.2 Buffer Tank

A variety of buffer tanks were investigated for this project, including tanks marketed by the heat pump manufacturers for use with their products, third-party hot water storage tanks marketed for domestic hot water systems, and buffer tanks for solar thermal systems with integral heat exchange surfaces. When a heat exchanger was needed we found that a simple storage tank and separate heat exchanger were more cost effective than a buffer tank with built-in heat transfer capabilities. While each site elected to use a different buffer tank, the buffer tank capacity varied between 40 and 80 gallons.

The following buffer tanks were installed at each of the demonstration sites:

- Sapsucker Woods Road: 40 Gallon (Solstice, marketed for heat pump)
- Firetower Road: 80 Gallon (Sanden, provided with heat pump)
- Riders Mills Road: 40 Gallon (Third Party: AO Smith – Storage Hot Water Heater Tank)*
- Steuben Valley Road: 80 Gallon (Third Party: Caleffi – Storage Tank)
- Garrett Road: 55 Gallon (Third Party: AO Smith – Storage Hot Water Heater Tank)

*changed to a Magic Box BMTB300L 80 Gallon system part way through the monitoring period

1.2.1.3 Distribution Components - Pumps

The existing distribution pumps continued to be used for all of the demonstration projects except the Firetower Road site. At Firetower Road, the owner elected to remove the existing pumps and modified our design to make use of the small circulating pumps built into the Taco X-Block heat exchanger.

While the main distribution pumps were unchanged or simply removed, additional small pumps were sometimes needed for circulation between the heat pump and buffer tank and/or injecting heat into existing distribution loops. There were a variety of pumps depending on the flow needed, presence of and pressure drop through a heat exchanger, and desired level of speed control. Suitable pumps were readily available off the shelf, and they were selected by the installer based on availability, cost and convenience.

The Garrett Road site was the only new installation that needed a pump that could not be readily purchased at a local supply house. The Solstice Extreme is rated at 12 GPM, which can require a high capacity pump when paired with a high head loss plate heat exchanger. For the Garrett Road site a suitable pump was selected, ordered from an online retailer.

1.2.1.4 Distribution Components - Heat Exchangers

The Solstice Extreme heat pump requires that a water-glycol mix be used in sections of the system exposed to outdoor temperatures to protect against freeze damage. Several sites (Riders Mills, Sapsucker Woods Road) elected to use this water-glycol mix throughout their heating system and did not require a heat exchanger. The Steuben Valley and Garrett Road sites elected to install a heat exchanger between the outdoor portion of the system and the buffer tank, significantly reducing the amount of glycol needed and using water, which has better heat transfer properties, in the rest of the system.

The Garrett Road site made use of a Bell & Gossett heat exchanger, sized using the Bell & Gossett Xylem sizing program for specific operating conditions at the site. The Garrett Road site eliminated the heat exchanger from the system and converted to a water-glycol mix (70% water to 30% propylene glycol) part way through the demonstration period as a way to increase the maximum supply temperature delivered from the heat pump. The heat exchanger for the Steuben Valley Road site was selected by the owner.

Figure 6: Xylem heat exchanger sizing report

Screenshot of performance metrics from the design report for the Garrett Road site

	Hot Side		Cold Side	
Fluid Name	Ethylene Glycol		Water	
Temperature(°F)	130.00	121.36	103.87	120.00
Connection ID(in)	0.6300	0.6300	0.6300	0.6300
P Drop(PSI)	4.18		0.94	
P Drop Nozzle(PSI)	0.87		0.21	
P Drop based on port (PSI)	0.33		0.08	
Shear Stress(pa)	128.08		28.90	
Mass Flow Rate(lb/hr)	6,197.55		2,972.82	
Nozzle Velocity(ft/s)	12.37/12.34		6.16/6.19	
Channels	1*14		1*15	

The Firetower Road site, which had a Sanden SanCO2 unit installed, uses potable water as the liquid circulating through the outdoor portion of the system. This water does not require a heat exchanger to isolate it from the other potable water systems in the building, but does require separation of the potable water from the heating water side of the system. Sanden mandates the use of a specific combination pump, control and heat exchanger component called the Taco X-Block when using their heat pump as part of a heating system.

Figure 7: Sanden Required Supplemental Equipment

Screenshot of manufacturers PowerPoint presentation

1.2.1.5 Distribution Components - Controls

Packaged controls are provided with both the Sanden and Solstice heat pumps to handle standard operations, such as triggering the unit to deliver heat as well as functions to prevent operation that might damage the heat pump.

It should be noted that the installation, programming and operation instructions available, both online and shipped with the unit, were limited and generally insufficient to make the adjustments necessary to operate the unit efficiently in a retrofit situation. It took our installer a significant amount of time and trial-and-error to get the controls working in a satisfactory manner.

When integrating an air-to-water heat pump into an existing system, we found that additional controls were required to handle backup heating system staging, reset controls, and multiple zone demands. Each site had different expectations and requirements, and a variety of controls approaches were taken.

Table 2: Heating staging controls used in this demonstration project

Controls installed at the different sites involved in this demonstration project.

Site	Heating Staging Controls	Notes
Sapsucker Woods Road	HBX Eco 550, integral controls on boiler	Offsite owner, needs to operate on its own, seamlessly
Firetower Road	Integral controls on instant hot water heaters, no actual controls integration. Taco X-Block cycles pump speed and operation to meet setpoint.	Boiler setpoints adjusted by owner as needed to supplement the heat pump. Additional heating systems on upper floors
Riders Mills Road	Manual switchover	Experienced Owner
Steuben Valley Road	Manual switchover	Experienced Owner
Garrett Road	Outdoor reset controller with relays to trigger different systems and pumps	Experienced Owner, outdoor trigger setpoint adjusted manually

1.2.1.6 Heat Emitters

While some existing systems, particularly radiant floor, are suitable for use with low temperature hot water, we observed that most systems that were previously used with 180F supply water required adjustment, and in some cases supplemental heat emitters. This was not always due to an inability to deliver the required heat, but sometimes a result of temperature imbalances caused by reducing flow rates that were noticeable at lower temperatures.

Three of the five demonstration sites had existing radiant floor systems and did not require additional output capacity. The two sites with conventional baseboard radiation were Sapsucker Woods Road and Garrett Road. The Sapsucker Woods Road site elected not to supplement the existing system for a variety of reasons including cost and minimizing occupant disturbance. The Garrett Road site had existing temperature imbalance issues and chose to install supplemental heat emitters in the form of a panel radiator in one room and section of staple-up radiant floor in two spaces that had been underheated.

1.2.2 Air-to-Water Heat Pump Selection Matrix

Table 3: Air-to-water heat pump units used in this demonstration project

Equipment metrics summary/comparison table for units that were selected for installation as part of this demonstration project.

Make, Model, Reliability		Cost Indoor+ Outdoor	Features			Performance Metrics	
Manufacturer	Sanden	Purchased in April 2018 for: $3,990	**Single phase?**	Yes	Notes and Features Heating use only allowed if installed as combination DHW and heating system, with at least 25 gallons of DHW use per day Heating capacity is only ~8,000 Btuh (full capacity not available for prolonged use due to defrost requirements)	**Nameplate Capacity**	15,400 Btuh
Unit ID (Model)	SanCO2		**Refrigerant Type**	uses CO_2 as refrigerant		**Capacity at 0F**	Maintains full capacity down to -15F, at -20F drops to ~12,000 Btuh
Number of Past Installations	Several hundred		**Max Supply Temp. (F)**	Up to 149F in heating, 170F in latest model. System only able to operate when return water temperatures are kept below 130F		**Efficiency**	Avg. 4.5 COP COP at -20F ~1.7-1.8, Max COP 5.2
Warranty?	Yes, 3yr labor, 10yr parts, 15yr tank					**Min. Oper. Temp. (F)**	-15F
Source:	https://www.sandenwaterheater.com/for-professionals/						
Manufacturer	Solstice (SpacePak)	The Solstice Extreme retails for $7,100.	**Single phase?**	Yes	Notes and Features Has a spot for immersion heater for backup heating	**Nameplate Capacity**	48,000 Btuh
Unit ID (Model)	Solstice Extreme (LAHP48 series)		**Refrigerant Type**	R-410a		**Capacity at 0F**	Just under 40,000 Btuh at 5F, 120F supply water
Number of Past Installations	About 1,200		**Max Supply Temp. (F)**	Up to 140F. System only able to operate when return water temperatures are kept below 130F		**Efficiency**	up to 4 COP
Warranty?	Yes, 1 yr parts , 2 yr compressor					**Min. Oper. Temp. (F)**	as low as 0F (with 120F supply temp)
Source:	http://spacepak.com/products/solstice-heat-pumps.asp						

1.2.3 Evaluated, but not used, Air-to-Water Heat Pumps

Table 4: Air-to-water heat pump units reviewed and evaluated but not used

Some of the units below were presented to building owners as design options when criteria such as installed cost made them a viable option. It should also be noted that units presented at the end of the table were investigated and found to be unavailable for purchase in the US, and therefore were not recommended for any site. Some units are missing metric data since they were eliminated from the comparison at an early stage of the process. Additional heat pumps expected to become available, or have recently launched, are listed in Appendix B

Make, Model, Reputation/reliability		Cost Indoor+ Outdoor	Features			Performance Metrics	
Manufacturer	Electro Industries (NorAire)	~$10,000 for fully installed system	**Single phase?**	Yes	Notes and Features Includes external gas boiler interface. Bluetooth control (per website) May not require buffer tank *Max is supply temperature is ~100F without electric backup. With electric backup - goes up to 180F	**Nameplate Capacity**	3,4,5 ton
Unit ID (Model)	NorAire		**Refrigerant Type**	R-410a		**Capacity at 0F**	50-60,000 Btuh (with electric supplemental heat)
Number of Past Installations	Not a lot		**Max Supply Temp. (F)**	~100F*		**Efficiency**	Rating for -12F design day is 1.73 COP
Warranty?	Yes					**Min. Oper. Temp. (F)**	-20F
Source:	http://www.electromn.com/gen/noraire.htm						
Manufacturer	Aermec		**Single phase?**	Yes	Notes and Features Optional electric heater, antifreeze, Reduced starting current (soft start), silent operation Capacity varies – per manual: at -20C (-4F) capacity of largest is ~18,900 Btuh (at 50C supply temp) Efficiency varies: per chart in the manual 1.25 to 3.7 COP at 55-60C output temp *largest unit can go only up to 130F	**Nameplate Capacity**	2.5-4 tons
Unit ID (Model)	ANK		**Refrigerant Type**	R-410a		**Capacity at 0F**	~18,900 Btuh (at 50C supply temp)
Number of Past Installations	In the hundreds		**Max Supply Temp. (F)**	Up to 140F*		**Efficiency**	1.25 to 3.7+ COP at 55-60 C output temp
Warranty?	Yes 1 year parts					**Min. Oper. Temp. (F)**	-4F
Source:	http://www.aermec.us/products-home/2015-06-11-14-07-23/ank						

Make, Model, Reputation/reliability		Cost Indoor+ Outdoor	Features			Performance Metrics	
Manufacturer	Nordic	ATW 75 is $6,868	**Single phase?**	Yes	Notes and Features Advanced controls with backnet interface Typical supply water temperature range is 100-115F	**Nameplate Capacity**	2-6 tons
Unit ID (Model)	ACE/ ATW		**Refrigerant Type**	R-410a		**Capacity at 0F**	under 30,000 Btuh, loop temp slightly over 100F
Number of Past Installations	Roughly 100		**Max Supply Temp. (F)**	up to 120F		**Efficiency**	3.7 COP @ 45F, 1.3 COP @ -20F
Warranty?	Yes 5 years					**Min. Oper. Temp. (F)**	-20F
Source:	http://www.nordicghp.com/product/nordic-products/air-source-heat-pump/air-to-water/						
Manufacturer	Chiltrix	Pricing for CX-30 $3,400	**Single phase?**	Yes	Notes and Features Cooling mode is reported better than competitors. *The heating capacity is given at 95F outlet water temperatures and drops from 30.5 kBtuh at 43F OAT down to 20 kBtuh at 17F OAT. Capacity at 113F supply water drops from 45.5 kBtuh at 77F OAT, to 12.15 kBtuh at -4F OAT.	**Nameplate Capacity**	At 95F supply water temp. 30.5 kBtuh*
Unit ID (Model)	Cx30		**Refrigerant Type**	R-410a		**Capacity at 0F**	Capacity at 113F supply water drops to 12.15 kBtuh at -4F OAT.
Number of Past Installations	In US ~200 installations		**Max Supply Temp. (F)**	Up to 131F		**Efficiency**	1.66 COP @ -4F, 2.5-4.1 COP @ 50F (86F-131F LWT)
Warranty?	Yes - 2yr compressor 5yr all other components					**Min. Oper. Temp. (F)**	-4F
Source:	http://www.chiltrix.com/documents/						
Manufacturer	EcoLogix		**Single phase?**	Yes	Notes and Features COP in the high 4's at standard operating temperature and pressure COP 3 @ 17F COP 1.8 @-13F	**Nameplate Capacity**	58-68 kBtuh
Unit ID (Model)	A2W540-D-LI A2W600-2-LI		**Refrigerant Type**			**Capacity at 0F**	22-36 kBtuh at -13F OAT
Number of Past Installations			**Max Supply Temp. (F)**	104F		**Efficiency**	Varies, COP in the high 4's at STP
Warranty?	Yes 2 years+					**Min. Oper. Temp. (F)**	-13F
Source:	http://ecologix.ca/products/cold-climate-heat-pumps/						

Make, Model, Reputation/reliability		Cost Indoor+ Outdoor	Features			Performance Metrics	
Manufacturer	Artic Heat Pumps	outdoor unit: $3,248 $4,560 $5,360 Storage tanks with electric backup ~$2,000	**Single phase?**		Notes and Features currently out of stock	**Nameplate Capacity**	
Unit ID (Model)	Three models: 29,000 48,000 & 60,000		**Refrigerant Type**			**Capacity at 0F**	
Number of Past Installations	Unknown		**Max Supply Temp. (F)**			**Efficiency**	
Warranty?						**Min. Oper. Temp. (F)**	
Source:	https://www.arcticheatpumps.com/buy-cold-climate-heat-pump/heat-pumps.html https://www.arcticheatpumps.com/buy-cold-climate-heat-pump/storage-tanks.html						
Manufacturer	Fujitsu		**Single phase?**	Yes	Notes and Features No US models available. Unit has option of supplemental heater (electric) Can provide up to two zones with different temperature water	**Nameplate Capacity**	Up to 14kW in single phase
Unit ID (Model)	Waterstage		**Refrigerant Type**			**Capacity at 0F**	
Number of Past Installations			**Max Supply Temp. (F)**	Up to 140F		**Efficiency**	Slightly over 4 COP at 7C OAT
Warranty?						**Min. Oper. Temp. (F)**	-4F
Source:	http://www.fujitsu-general.com/global/support/downloads/erp/lot-1/index.html						
Manufacturer	Panasonic		**Single phase?**	Yes	Notes and Features Does not appear to be available in the US	**Nameplate Capacity**	Up to 12 kW in single phase
Unit ID (Model)	Aquarea SXC		**Refrigerant Type**			**Capacity at 0F**	Unclear – larger unit (16kW) maintains capacity to -15C
Number of Past Installations			**Max Supply Temp. (F)**	Up to 131F		**Efficiency**	Up to 5 COP
Warranty?	Yes 5 years					**Min. Oper. Temp. (F)**	-4F
Source:	http://www.aircon.panasonic.eu/GB_en/ranges/aquarea/						
Manufacturer	LG		**Single phase?**		Notes and Features Has an indoor unit, but no single phase outdoor unit yet	**Nameplate Capacity**	
Unit ID (Model)	ThermaV Hydrokit		**Refrigerant Type**			**Capacity at 0F**	
Number of Past Installations			**Max Supply Temp. (F)**			**Efficiency**	
Warranty?						**Min. Oper. Temp. (F)**	

Make, Model, Reputation/reliability		Cost Indoor+ Outdoor	Features			Performance Metrics	
Source:	http://www.lgethermav.com/overview/EN/LGThermaV_sub01.html						
Manufacturer	Daikin		**Single phase?**		Notes and Features Removed from the North American market	**Nameplate Capacity**	
Unit ID (Model)	Altherma		**Refrigerant Type**			**Capacity at 0F**	
Number of Past Installations			**Max Supply Temp. (F)**	Up to 176F		**Efficiency**	
Warranty?						**Min. Oper. Temp. (F)**	
Source:	https://www.daikin.com/products/ac/lineup/heat_pump/index.html						
Manufacturer	Emerson		**Single phase?**		Notes and Features Emerson provides components for systems (not plug and play), but is reportedly known for large commercial installation. Reportedly has high supply temperatures	**Nameplate Capacity**	
Unit ID (Model)			**Refrigerant Type**			**Capacity at 0F**	
Number of Past Installations			**Max Supply Temp. (F)**			**Efficiency**	
Warranty?						**Min. Oper. Temp. (F)**	
Source:	http://www.emersonclimate.com/europe/en-eu/Market_Solutions/Residential/Heating/Pages/Refrigerant_Considerations.aspx						
Manufacturer	Aqua Products Company		**Single phase?**		Notes and Features In design/redesign	**Nameplate Capacity**	
Unit ID (Model)	RCC (Reverse Cycle Chiller)™		**Refrigerant Type**			**Capacity at 0F**	
Number of Past Installations			**Max Supply Temp. (F)**			**Efficiency**	
Warranty?						**Min. Oper. Temp. (F)**	
Source:	http://www.aquaproducts.us/reverse-cycle-chiller.html						
Manufacturer	Mitsubishi		**Single phase?**		Notes and Features Units not available in US, and no predicted timeline for their availability	**Nameplate Capacity**	
Unit ID (Model)			**Refrigerant Type**			**Capacity at 0F**	
Number of Past Installations			**Max Supply Temp. (F)**			**Efficiency**	
Warranty?						**Min. Oper. Temp. (F)**	
Source:	https://www.mhi-global.com/products/detail/heat_pump_web_catalog.html						

2 Site Selection

2.1 Summary

Site selection was a rigorous process in which a large initial set of interested applicants were recruited, and then screened for suitability through multiple stages of review. This included site inspections on a smaller subset of sites at the latter stage of selection. It culminated with an energy analysis, cost estimate, and schematic design proposal for one or more air-to-water heat pump solutions at each site.

From a pool of over 50 interested applicants, the most promising sites were selected. Eight in-depth site visits were made to collect additional data needed for preliminary design and to confirm the suitability of each site. This data was used to complete a heat load calculation for the site, select a heat pump system, develop a scope of work, and present the owner with design options and preliminary cost estimates.

This last stage proved to be problematic as this demonstration project encountered difficulties in finding sites in which the technology was a cost-effective solution. Only two from the pool of 50 decided to proceed with the project. The homeowners who participated were motived by a desire to reduce carbon emissions.

To reach the five-site target, two sites that had installed an air-to-water heat pump prior to the start of this study were recruited, and the restrictions on wood heat were relaxed, allowing a previously excluded site to participate.

Table 5: Sites investigated for this demonstration project

Design and analysis completed for sites involved in this demonstration project, and final involvement determination.

Site	Status	Notes
Sapsucker Woods Road	Demonstration Participant	Retrofit Installation.
Firetower Road	Demonstration Participant	Retrofit Installation. Only site to select the Sanden
Riders Mills Road	Demonstration Participant. Existing Installation.	Previously Installed – Monitored and inspected as part of this project
Steuben Valley Road	Demonstration Participant. Existing Installation.	Previously Installed – Monitored and inspected as part of this project
Garrett Road	Demonstration Participant	Retrofit Installation. Supplemental wood heat.
Bradshaw Road	Analysis and Design completed. Owner elected not to pursue	New Construction Site – Analyzed and interested. Decided not to participate
Cayuga Heights Road	Analysis and Design completed. Owner elected not to pursue	Multi-story site with existing temperature imbalance issues and in need of a new heating system
Bostwick Road	Analysis and Design completed. Owner elected not to pursue	Small site, with PV being installed. System to provide Domestic Hot Water in addition to heating.
Ringwood Court West	Analysis and Design completed. Owner elected not to pursue	Small site with existing propane heat. Rental property in need of a new heating system.
Blackstone Ave	Analysis and Design completed. Owner elected not to pursue	Existing radiant floor heat and investigating solar PV. Existing natural gas heat results in negative monthly cost savings
Luce Road	Analysis and Design completed. Owner elected not to pursue	Large site with relatively modern house. Open to some distribution supplementation
Forest Home Drive	Analysis completed. Owner elected not to pursue	Large site, would require multiple heat pump systems and substantial modifications to existing heating system.

2.2 Observations and Lessons Learned

The sections below document barriers encountered to finding appropriate sites for this technology, and when appropriate, the methods or approaches adopted that circumvented those barriers.

2.2.1 Competing with Existing Technology

While identifying and evaluating sites for this project, we discovered that in many cases, the cost to purchase and install an air-to-water heat pump could not compete with the purchase and installation costs of an equivalent air-to-air heat pump or high efficiency boiler system. All three competing technologies had similar operating costs, and so the lower installed cost systems were financially more attractive options.

As a new technology, and one that operates at a reduced capacity with colder outdoor temperatures, we required that backup heat be installed or left in place for each site. This was an extra cost that was not needed for most competing systems; residential boilers can reasonably be expected to be repaired or replaced within a day of failure, and many air-to-air heat pumps are equipped with integral electric heating elements to ensure that a minimal heating capacity can be maintained.

Even with a financial incentive provided by the project to offset the additional cost of the air-to-water heat pump, we discovered that local heating and plumbing contractors had a strong preference to continue working with systems that were tried and proven. Some homeowners were willing to install an air-to-water heat pump, but they were talked out of it by their installation contractor in favor of a more conventional system.

2.2.2 Economic Viability: Fuel Costs

With the current fuel costs, conversion from natural gas to electric heat using air-to-water heat pumps is difficult to do cost effectively. At least one of the sites that was evaluated with natural gas heat would have increased utility bills after installing an air-to-water heat pump system. This limited the project to sites that use oil, propane or electric for their heat.

The site selection methodology initially excluded sites with wood heat due to the difficulty in accurately determining wood heat contributions to the heating load. Many of the owners who were interested in pursuing alternative heating systems were located outside natural gas service areas, and they had already invested in some form of supplemental or backup wood heat.

2.2.3 Types of Homeowner Interested

The type of homeowner interested in installing and using an air-to-water heat pump typically had a strong desire to move away from their conventional heating system, and most cited a desire to eliminate or reduce fossil fuel consumption as a leading driver.

Some homeowners had failing heating systems, and they thought that participation in this demonstration project would be a cost-effective replacement solution. However, the economics were such that other options were generally more cost-effective, and these homeowners elected not to pursue participation.

Several homeowners lost interest when it became clear that the most effective design would make use of their existing heating system as a backup, and the existing system would take over at low outdoor air temperatures, when the heat pump would be unable to carry the heating load. This was unappealing to the sites with failing existing systems and to homeowners who wanted to divest from fossil fuel use entirely.

This left a relatively small population who were interested in participating. Within that group, the homeowners were generally highly technical first adopters and hands-on/Do-It-Yourself people. This group proved to be a good fit for the technology, as most sites required ongoing adjustments to continue optimizing operation beyond the default settings.

2.2.4 Ideal Candidate Site

The expectation was that the ideal candidate site would be a small, well-insulated new construction home, with low-temperature radiant floor or similar heat emitter system, looking for a non-fossil fuel heating and/or domestic hot water solution, and interested in pursuing a new technology.

We were approached by a site that matched nearly all those criteria. The site homeowner had independently started researching air-to-water heat pumps and wanted to work with the project team to develop a design. A schematic layout was developed for a low temperature radiant floor system, and a buffer tank was selected that would also provide pre-heating of the domestic hot water. The homeowner selected a decorative propane fireplace with sufficient capacity to provide backup heat.

Unfortunately, despite being a nearly ideal candidate, the homeowner decided to go with air-to-air heat pumps on the recommendation of their HVAC installer as a less expensive and more robust solution. Although the equipment costs for both systems were similar in order of magnitude, the components for the higher performing type of radiant floor they would need, since they decided not to go with a traditional high mass slab floor, for the air-to-water heat pump solution were simply not within their budget.

In contrast to our imagined ideal site, the project in which this technology was more cost effective than a comparable air-to-air system was the Sapsucker Woods Road site, a four-unit split-level apartment building. The building owner approached us after their primary heating boiler failed, interested in using an air-to-water heat pump to replace it.

While the building owner was also interested in moving away from oil heat, economics were the main driver for this project. The features that made the air-to-water system competitive with an air-to-air alternative were the existing hot water heating system infrastructure, and the large number of individual zones that would each need to be served by an individual indoor head if using an air-to-air heat pump system. With a separate head needed for the main living space and each bedroom, there would have been a minimum of ten indoor heads required for this relatively small site.

One issue with installing a new technology such as an air-to-water heat pump to replace a failing heating system failure is the extended design, procurement and installation time needed for the new system. The building owner resolved this by installing a backup electric boiler as initial replacement for temporary use while the heat pump system could be designed and installed.

To overcome the obstacle of disinterested local installers, Taitem provided design and installation support. For the four-unit building the owner was able to do the installation with Taitem support instead of contracting with an independent contractor. This significantly reduced the costs associated with installation and familiarized the maintenance staff with the air-to-water heat pump system.

3 Retrofit Planning

3.1 Summary

The retrofit planning and site selection phases of this project had some significant overlap. Once sites were confirmed to meet the general screening criteria, the final stages of screening were also the initial stages of planning and design.

Each candidate site underwent a site visit by a senior engineer. Key information regarding the site was collected, including details about building envelope and footprint, and also the owner's motivation for participation in the project. Conditions and features of the existing heating system and current utility use patterns were collected. This information became the basis for an extensive preliminary design and planning process.

With the information gathered, an HVAC design tool (HAP) was used to model the site and perform hourly simulations of different proposed designs. The model was validated by a simulation of the existing system with the utility bills. Once validated, two specific points of data were extracted from the model. These were the maximum heating load (magnitude, as well as when it occurred and for how long) and annual energy consumption.

This allowed us to understand how large the proposed system would need to be to ensure occupant comfort and how the proposed system would compare with the existing system. Various combinations of heat pump, existing heating system and supplemental heating systems were simulated and the most cost-effective and suitable options for each site determined. For all of the sites we analyzed, selecting an air-to-water heat pump to handle the full peak heating load was never the most cost effective option.

In conjunction with the hourly simulations, a second set of calculations was completed. The heat load for each room at a number of outdoor air temperatures (-10F, 0F, 10F, 20F, 30F) was collected and recorded for use in a manual calculation. Because the air-to-water heat pumps are unable to deliver water at temperatures as high as most of the existing heating systems, we had to ensure that the heat emitters in the space would be able to sufficiently heat each room.

The length and output capacity of the existing baseboard, radiant flooring, or other heat source were measured at the site and spreadsheet calculations completed to determine how much heat could be delivered to each room at the reduced water temperatures, and this was compared with the expected heating load for that space at different outdoor conditions. The ability to deliver heat with low temperature to the space proved to be more limiting than the heat pump nominal capacity and the existing radiators determined when backup heat was needed.

These calculations informed the selection of the most suitable heat pump for each site, and they were the basis of the energy and cost savings predictions provided to the owner. Once one or more suitable heat pump systems had been established, a cost estimate could also be created. This estimate included the equipment cost for the heat pump and known accessories, as well as costs for supplemental heating elements, contractor labor, controls and programing, and other necessary elements for the full system installation.

It should be noted that multiple options were provided to most sites. Typically, the most efficient, or best performing system, was not the most cost-effective, and sometimes the best long-term proposal had a prohibitive first cost. These considerations were documented, along with potential limitations of the proposed systems and high level background on the systems (such as images of the components and major components list). This was presented to project team, and once approved, to the site owner.

Table 6: Air-to-water heat pumps used in this demonstration project

Air-to-water heat pumps installed at the different sites involved in this demonstration project.

Site	Heating System Selected	Notes/Status
Sapsucker Woods Road	Solstice Extreme	Retrofit Installation.
Firetower Road	Sanden SanCO2	Retrofit Installation. Only site to select the Sanden
Riders Mills Road	Solstice Extreme	Previously Installed – Monitored and inspected as part of this project
Steuben Valley Road	Solstice Extreme	Previously Installed – Monitored and inspected as part of this project
Garrett Road	Solstice Extreme	Retrofit Installation.

Once a preliminary design was accepted by the owner, and a site committed to being involved in the demonstration, each project typically went through an additional round of planning and design. A final schematic design was presented to the owners and installation team prior to the start of any on-site work, however design modifications extended through installation and some modifications continue at several of the sites.

3.2 Observations and Lessons Learned

The installation costs quoted by local installers for these systems included a large safety factor to cover learning about the systems and lack of familiarity, and trust, in the technology. This is a typical practice for new technologies. While there are additional costs associated with working with a new technology, it is difficult for a homeowner to shoulder the increased cost. Future demonstrations could seek to mitigate this by providing an incentive to the installer to cover the additional learning time. Contractors were also concerned about equipment malfunction and callbacks.

These costs should go down as these units become more common. In the short term, they are creating an artificial deterrent to their adoption, simply by negatively impacting the cost-effectiveness of installing air-to-water heat pumps versus other more widely adopted technologies, such as air-to-air heat pumps and high efficiency boilers.

As noted before, the type of homeowner interested in installing and using one of these units was typically a highly technical early adopter/hands-on/Do-It-Yourself type person.

One trait of this type of owner was a high level of interest and involvement in the design and installation. None of these installations were simple, and most went through several iterations as new components or ideas were introduced that the owner was interested in including as part of the project. Although not tracked as such, it can be reasonably estimated that design time and installation labor costs were more than doubled as a result of owner involvement as compared to a project with a less involved owner.

The design of most sites went through several revisions as design goals, objectives and available equipment evolved. The Firetower road project, for example, went through eight different released design permutations, most involving the relocation of the two existing boilers and addition/removal of radiant floor zones from the system. This was challenging to the design team, and it would be unfeasible for an installing contractor.

4 Retrofit Execution

4.1 Summary

Installation of two of the demonstration sites were completed by the homeowners prior to inclusion in the study. Taitem led the installation on the other three sites. Installation had been expected to be performed by local contractors, with Taitem conducting schematic design and limited construction stage support. However, contractor involvement proved to be an obstacle, and Taitem expanded its role to ensure high quality installations for the project.

Table 7: Installation work completed for the demonstration project

Installation completion dates and work performed by installer for the different sites involved in this demonstration project.

Site	Installed By	Installation Date	Notes/Status
Sapsucker Woods Road	Taitem and Owner	Apr-May 2018	Retrofit Installation.
Firetower Road	Taitem	Oct-Nov 2018	Retrofit Installation. Only site to select the Sanden
Riders Mills Road	Owner	Existing	Previously Installed – Monitored and inspected as part of this project
Steuben Valley Road	Owner	Existing	Previously Installed – Monitored and inspected as part of this project
Garrett Road	Taitem	Dec 2018-Jan 2019	Retrofit Installation.

While the installations are complete at all sites, there are ongoing modifications and additions by the owners at all sites except Sapsucker Woods Road.

4.2 Observations and Lessons Learned

4.2.1 In-progress changes

Despite working with a complete design, mid-installation changes still occurred. Some of these modifications were due to the continuing evolution of homeowner expectations. Others changes were triggered by unforeseen existing conditions that were not as expected from preliminary field documentation. The remaining mid-construction changes were due to unforeseen limitations of equipment, particularly the control systems, which were not clear from the available documentation.

Ways of mitigating or addressing issues associated with greater than anticipated levels of in-progress alterations are as follows:

- Homeowners with continually evolving goals and expectations are a reality with all projects, but the issues are more pronounced on new technology demonstration projects. The best way to mitigate issues and manage expectations is frequent communication between all members of the project team.
- Uncertainty regarding existing conditions can be mitigated by understanding the elements that can lead to unexpected problems with air-to-water heat pump installations, such as high water temperatures or flow rates, or underheated spaces, and including those in a standard scoping visit.
- In addition to learning about air-to-water heat pump system components and their optimal configuration, addressing controls setup and integrating the backup heat and existing system operation are key factors to a successful installation.

4.2.2 Adjustments and optimization

Optimization of the air-to-water heat pump installations is ongoing at all sites. Reasons include:

- This is an early technology, and there is not a lot of data about operating best practices and appropriate settings for all but the most basic applications. The default settings are not likely to be optimal in many situations. As a result, these systems need more adjustment before they are fully optimized for each site.
- The homeowners who are interested in this new technology are also interested in continual experimentation and improvement. This experimentation, when done in a logical manner, should improve performance at their sites. Although each site will be unique, settings that are found to be effective at one site are helpful to the implementation at other sites.
- Although we had a good universal approach, each project was, within those general parameters, very unique. Details that would be minimally important for a boiler retrofit become more impactful in an air-to-water heat pump system. These include distribution system flow rate, pump speeds, temperature drop in supply and return water, undersized and oversized zones, ability to work with the existing system controls, and other factors.

4.2.3 Installation instructions

Air-to-water heat pumps are a new technology, with a limited number of existing installations, and no local heating and plumbing contractors with installation experience. There was no local support network for troubleshooting or setup questions, nor local experts to call with questions. That made the technical support provided by the manufacturers vitally important.

Unfortunately, our experience with both Solstice and Sanden was that the manufacturers' support was limited. When the main heat pump unit was delivered to the site, it came with poor quality documentation and limited installation instructions. We found at least one instance in which the manual that had been shipped with the unit was for a different generation of system and contained information and wiring diagrams that were no longer accurate.

When we talked with the manufacturers' technical support teams, we experienced mixed results. Not many were familiar with the units, and at times we received inaccurate information. For complicated questions we needed to schedule a call back for more involved troubleshooting. Eventually, we developed specific technical contacts with the manufacturers which was key to getting accurate information.

Anecdotally, we were informed that one of the reasons that an air-to-water heat pump from a well-known air-to-air heat pump manufacturer was taken off the market was because of limited demand and the high cost of technical support needed. This indicates that providing the increased technical support required to make air-to-water heat pumps a viable solution for homeowners will continue to be a challenge.

4.2.4 Project hand-off and Service

Field training was conducted between the installing hydronics engineer and homeowner. This occurred during installation and subsequent adjusting and fine-tuning work. The homeowners were very involved in the installation process and were introduced to the operation, control and basic setup of their systems.

In general, the homeowners already had a fair understanding of the system and basic to advanced knowledge of HVAC principles. Several were HVAC design professionals and one was a mechanical contractor. Taitem has been back to all three Taitem-installed sites to assist the homeowners with equipment issues that occurred during the first heating season, regardless of the experience level of the owner.

One issue with Taitem stepping in to perform installation of these systems is that it replaced work that would have otherwise been performed by a local contractor. It would have been preferred that a local contractor worked with Taitem to conduct the installations and then they would be able to provide service and support for these units moving forward. While Taitem gained significant experience doing these installations, we need to pass this knowledge to the contracting market. Currently, there are no local contractors who have worked on air-to-water heat pumps, and few who are interested in learning.

Shortly after each unit was installed and operational, generally within a week of installation, we observed that most homeowners had started making adjustments to different setpoints, either on the unit, or as part of their distribution system. As a best practice, the installer should make a record of all setpoints and control settings during three points: 1) documenting the received default settings, 2) after the initial installation, and 3) prior to leaving the site. This record allows the unit to be restored to ‘as-installed’ condition.

5 Site Specific Narratives

Additional documentation, the final schematic design drawing, site photographs and floor plan documentation for each site are included in Appendix A.

5.1 Sapsucker Woods Road

Figure 8: Sapsucker Woods Road- Elevation Photo

View of the site from the driveway. Upper and lower entrances visible, garage and near side windows (note larger upper story windows).

5.1.1 Site Description

This demonstration site is a rental property with four separate apartments. The building is a two story, split level house, and each floor has one 3-bedroom and one 1-bedroom apartment. A single, common heating system serves all four apartments and is located in the attached garage.

Table 8: Sapsucker Woods Road – At-a-glance Site Metrics Table

Summary of characteristic features for the Sapsucker Woods Road site.

Building Size:	4,025 SF
Heating Load:	83,000 Btuh (Existing heating system) 60,000 Btuh (Peak heating load)
Mechanical System:	The building is hydronically heated, with two zones, one for the bottom floor, one for the upper floor. Each zone covers two apartments, with controlling thermostats located in the 3-bedroom apartment. Pre-retrofit, the building was heated by a natural gas fired boiler. However, once it failed, it was converted to an electric boiler. There is no central cooling system.
Energy Efficiency of the Building:	Condition of Envelope: Considered to be standard code compliant construction, average air tightness Energy efficiency recommendations: insulate closet containing buffer tank. Investigate high thermostat setpoints for certain apartment (and consider adding upper limit to setpoint range).
Unique Features and Owner Motivations	The owner approached Taitem after the existing natural gas fired boiler failed. Driving forces were a combination of financial and efficiency. Alternate systems that the owner obtained quotes for included an air-to-air heat pump system and one-for-one replacement of the gas fired system

5.1.2 Factors for Success

Key factors for success at this site included:

- Willing building ownership
- Existing relationship with installer (in-house)
- High density of interior zones (more of zones per square foot than most sites)
- Existing hydronic distribution system, confirmed able to run at low temperature
- Existing electric backup system

5.1.3 Demonstration Site Evolution

What started as an urgent owner inquiry for engineering support for a rental property turned into a surprisingly well suited demonstration site with an owner open to installing an emerging technology, and the discovery of an unexpected cost effective application of the air-to-water heat pump.

Initially, this site seemed like a poor candidate for participation in this demonstration project. There were financial and schedule constraints that would be difficult to meet, and the multi-unit building with offsite ownership was considered to be a complicating factor.

The first concern was the timeline: the owner needed an immediate solution to deliver heat to building tenants, and the air-to-water heat pumps required a significant amount of lead time, both for design and installation, as well as for procuring from a local distributer.

This was resolved when the owner decided that the best short-term solution was to install an electric boiler, which could then be used as a backup and low ambient heat source for the new system.

An additional concern was the cost of the air-to-water units. As with many new technologies, these units tend to be more expensive when compared with more established technologies such as air-to-air heat pumps. In this instance, the cost of the air-to-water unit was competitive with other technologies because:

- The building already had a hydronic infrastructure in place for the system. This improved the competitiveness of hydronic solutions versus air-to-air heat pumps.
- An electric boiler was already being installed as the quickest and cheapest replacement heating solution. This could be used to provide backup heat, and a new backup system did not need to be included in the cost.
- The building layout (split-level, multiple apartment) would have required a large number of replacement heating units to provide appropriate coverage and zoning.
- It became apparent that the owner was willing and interested in performing some or all of the installation himself, which had a significant impact on cost.

The concern with offsite ownership was twofold. First, air-to-water heat pumps systems have certain limitations on capacity and operation at low temperatures, and they need to be operated and controlled with an understanding of these limitations. This might not be something the occupants or maintenance staff were willing to accommodate. Air-to-water heat pumps deliver lower temperature water than most electric or gas fired boilers, which can reduce the ability of the existing distribution system to deliver enough heat to the space, even if the heat pump has sufficient capacity. For some building owners, limited periods of time when the space temperature drops by a few degrees are acceptable; however, in a rental situation, the landlord is contractually obligated to deliver enough heat to ensure occupant comfort under all conditions, and this flexibility is lost.

The installation of the electric boiler, and its subsequent use during the remainder of the heating season, provided useful information on the water temperatures that could satisfactorily heat the building under various load conditions. This showed that lower water temperatures were feasible, and it provided a tried and tested backup system capable of raising the water temperatures, if needed, to meet peak load conditions.

Working with the owner's locally-based staff during the installation of the new electric boiler, and while designing the optimal integration the proposed air-to-water heat pump, provided reassurance that they were capable and invested in the demonstration project. Involving the staff in the installation of the system ensured that the operation limitations were known and that maintenance could be done in house.

5.1.4 Site Design

5.1.4.1 Evaluating heating capacity of distribution system at various temperatures

An analysis of the existing distribution system was performed by Taitem. The length of active existing baseboard was documented, and the equivalent heat output at various average water temperatures was calculated using AHRI steam ratings and Modine performance tables (analysis included in Appendix A).

For this site, we also evaluated the impact of reducing flow velocity. Lower velocity will result in lower water temperatures being returned to the heat pump, which is good for efficiency. Lower velocity also decreases the average water temperature, indirectly reducing distribution system heat output for a fixed supply water temperature. This effect on the distribution system output was accounted for in the design.

5.1.4.2 System Sizing

When the building owner installed the new electric boiler, we were able to get indoor and outdoor air temperature measurements, boiler run times, and other metrics needed to define the building's heating slope. This allowed us to understand how the building was performing, beyond what we could determine from modeling alone. An engineering model was prepared using HAP, and a combination of the two data sources was used to evaluate savings and heating load. Analysis is included in Appendix A.

5.1.4.3 Determining System Flow Rates and Control Sequences

A spreadsheet calculation was performed to determine the appropriate balance between lowering loop velocity to minimize return water temperature, and increasing the loop velocity to maximize distribution system output. The heat balance, and water temperature for key points on the system were calculated for a variety of outdoor air temperatures and combinations of boiler and heat pump operation.

The flow rate must be high enough to allow the distribution system to meet peak load conditions, and it must be low enough that a 10F or greater temperature drop across the loop can be maintained during conditions when the heat pump is running.

A spreadsheet was created to evaluate the loads and flow rate at different outdoor conditions (included in Appendix A), and an optimized flow rate of just over 5gpm was calculated that allows the heat pump to operate as the primary heat source down to 0F.

5.1.4.4 Evaluating Pump and Control Strategies

According to the manufacturer, the heat pump is controlled to maintain a set tank temperature. While the system was being installed, we discovered that the circulating pump between the heat pump and the buffer tank would run continuously if this control method was used. The packaged heat pump controller had sensors on the supply and return lines to the heat pump but did not have a sensor in the buffer tank. This meant that the return water temperature was used to indicate the buffer tank temperature, and the circulation pump needed to run continuously to ensure this temperature was reasonably accurate.

With the HBX control package that we installed to activate the boiler as a backup heat source, triggering it on when the heat pump was unable to maintain secondary loop water setpoint, we have the option to instead trigger the heat pump and circulation pump on when the apartment thermostats called for heat. This option can be used to prevent the pump from running unnecessarily, however it also prevents the tank from coming back up to temperature during low load periods, thereby limiting the effectiveness of the buffer tank as a reservoir of heat.

Having the additional heat stored in the buffer tank can allow the system to temporarily carry more of the building load than the heat pump could handle on its own. In essence, the buffer tank acts as a battery, which the heat pump can charge when the zones are not calling for heat. In an idealized simulation, the zones would call for heat in a linear fashion as the outdoor air temperature drops. In reality, thermostatically controlled zones cycle on and off as the temperature fluctuates by +/- 2F around setpoint. With this operating pattern, the buffer tank is a useful tool to smooth out that on/off operation into a more efficient, steady operating rate.

To determine which control approach we should use, a calculation was performed to estimate the amount of useful energy stored in the buffer tank. The result indicated that the amount of energy saved for every hour that the buffer tank was in use to cover a temporary spike in load was equivalent to the pump running unnecessarily for 30 hours.

The buffer tank is only useful under a certain set of circumstances however:

- When the heating load is less than the heat pump capacity, the buffer tank will have limited impact (some slight efficiency gains are possible)
- When the heating load is above the heat pump capacity by a significant amount, or for an extended period (more than 15 minutes) the buffer tank will have limited impact

In contrast, periods when the pump would run unnecessarily are essentially any time the thermostat is not calling for heat, which would be significant in the spring and fall.

The final implemented sequence was a compromise. It makes use of the HBX controller to trigger the heat pump and pump on/off with the building load, and uses a setting in the heat pump controller to continue running the unit for a limited time after each heating cycle. This will trigger the pump to continue running for a certain delay after the call for heating is released. This delay needs to be developed for each site, and depends on the typical cycling of the heat pump, and thermal mass of the system and buffer tank.

5.1.4.5 Evolving Delays and Setpoints

After installing the measurement and verification equipment, it was discovered that the electric boiler was being brought on for brief periods during each initial call for heat, even during mild, low load conditions when the heat pump was well within capacity range. It became apparent that the heat pump required more time than expected to reach setpoint. The resolution was the implementation of a longer 15 minute delay at the controller prior to bringing on the second stage of heat, the electric boiler.

Additional controls adjustments were made in response to feedback from the measurement and verification contractor, including: increasing delays to limit cycling and premature boiler operation; adjustments to the outdoor reset curve which lowered the supply water setpoint, allowing the heat pump to carry more of the load at lower outdoor temperatures; and releasing a few more conservative freeze protection safety measures that were setup prior to the system receiving full glycol charge.

A spreadsheet tracking the setpoints, defaults and changes for this site is included in Appendix A.

5.2 Firetower Road

Figure 9: Firetower Road- Elevation Photo

View of the North-West elevation. All three stories visible: site built into slope, basement only fully exposed along North side

5.2.1 Site Description

This demonstration site is a three story house, with the first level being a walk-out basement. The site has no natural gas, oil or propane, and was previously heated with a combination of: an electric boiler, serving radiant floor zones on the basement and first floor; air-to-air heat pumps serving select spaces on the first floor; and electric resistance heat in bathrooms and other spaces for on-demand heat. The proposed heat pump was designed for use to serve the basement, but evolved to potentially also serve the first floor radiant floor loops, and supplements the existing electric boiler.

Table 9: Firetower Road – At-a-glance Site Metrics Table

Summary of characteristic features for the Firetower Road site.

Building Size:	5,250 SF
Heating Load:	40,260 Btuh (Existing boiler) 14,000 Btuh (Calculated basement heating load)
Mechanical System:	Radiant floor heat with an electric boiler (11.8kW) in the basement. There are four zones installed, one for each floor and one for an indirect domestic hot water heater. The basement zone is the primary zone and we were informed it is the only zone currently used. There is supplemental electric resistance heat in the bathrooms, kitchen and a few other locations. The first floor living room is served by a ductless heat pump.
Energy Efficiency of the Building:	<u>Condition of Envelope</u>: Tight envelope with measured air leakage rate of 1,746 CFM50, wall and ceiling insulation varies, but is generally R-13 in walls, R-39 in ceiling <u>Energy efficiency recommendations</u>: No specific recommendations made. While additional insulation could be added and the 1st floor radiant system improved, it was not felt that these would be cost effective measures.
Unique Features and Owner Motivations:	Existing radiant floor and electric backup boiler allows low temperature systems to be used and removes concerns about providing electric backup to the system. Engaged and technically-experienced homeowner.

5.2.2 Factors for Success

Key factors for success at this site included:

- Involved and excited owner
- Efficient and low load house
- Existing, multi-zone low temperature hydronic system
- Existing electric heating systems available for backup

5.2.3 Demonstration Site Evolution

The Firetower road site is unique in that it was initially served by three different heating systems, all of which are electric powered and have overlapping coverage areas. The owner would run various combinations of the three systems depending on the ambient conditions and which areas of the house were currently in use. This made accurate modeling and extraction of past heating use from the utility analysis difficult.

The first system was an electric hot water boiler. This was primarily used to serve a radiant heating loop in the basement, but was also connected to a second radiant floor zone that served the first floor. As an isolated system serving the basement only, the heating load is relatively low, however if used to its full potential to serve both floors, and accounting for partial heating effects to the upper floors, the load could be increased significantly.

The second system was an air-to-air heat pump located in the first floor living room. It was reported to be the primary heat source for the first floor.

The third system was a series of stand alone electric heaters, primarily in the bathrooms, used to provide on-demand heat when the space is occupied, but kept off otherwise.

Our initial proposed design called for the installation of a larger air-to-water heat pump, which would be used to carry most of the house heating load serving the basement and first floor, and reducing the amount of heat load carried by the air-to-air heat pumps and spot electric space heaters.

A combination of factors, including price, curiosity about the CO_2 refrigerant system and desire to include domestic hot water generation in the project, caused the owner to select the Sanden unit, with the expectation that it would serve just the basement heating zone.

This approach was later modified at the owners request to allow the proposed system to also serve the first floor radiant floor zone. This exceeds the Sanden heating capacity at certain temperatures. The owner is continuing to work on fine-tuning the control sequence after the installation and may install a system that will enable or disable this second zone based on building load or outdoor air temperature as a future optimization. For our installation, the zones are manually controlled and currently serving the basement only, but can be adjusted as needed by the owner

5.2.4 Site Design

5.2.4.1 Layout Revisions

Over the course of the project the design was changed many times. This was primarily driven by the owner whose priorities for the operation evolved over time, leading to the relocation of the backup and booster heating systems. Additional modifications were conceived and carried out in the field during installation. These are documented based on field reports. Major changes were driven by the following:

- Changing priorities regarding freeze protection versus booster heating prioritization which altered the boiler locations.
- Efficiency and temperature concerns regarding the domestic hot water system led to an additional boiler relocation.
- Existing pumps were left in place to be re-used. Later it was decided that they would be replaced with new pumps, which evolved into the pumps being removed by the owner with no replacement. This relys on the built-in X-Block pumps for circulation, which are undersized for the existing system.
- Flow rate modifications for X-Block system continue to evolve in an effort to limit mixing in the buffer tank and reduce cycling.
- Revisions during installation were made to include additional heating zones which created conflicting system requirements with the previously unused zone. This required much higher supply temperatures and resulted in sub-optimal operating conditions, reducing efficiency and capacity.
- There were several owner mandated deviations from recommended design practices. The location of the mixing valve was changed, preventing it from providing scald protection; freeze protection heat trace was eliminated and replaced with a DC circulation pump; and water quality of the well-water being circulated through the unit was not tested which may impact performance over time.

The system may need further modification, as the domestic hot water side of the system appears to be building up thermally created pressure, causing the buffer tank pressure relief valve to release. This system is installed per manufacturers recommendations, and when contacted about this issue, the manufacturer stated that this was normal for their systems and not a cause of concern. We are recommending initial adjustments to the well pump pressure settings, followed by installation of an expansion tank if pressure build up continues.

The system also experienced a middle of the night fault condition, which prevented the unit from operating, and may have frozen elements of the unit. The fault condition appears to have been triggered by a control board failure, which then led to freeze conditions, and the owner was able to work with the manufacturer directly to address the situation under warranty.

The final pipe schematic is included below. A progression showing the evolution of the major layout revisions to date is included in Appendix A

5.2.4.2 Design Considerations: Freeze Protection

An unforeseen complication was the need for enhanced freeze protection at the site. Because this unit is designed to circulate domestic water directly, it prevents the use of glycol in the distribution loop between the outdoor unit and buffer tank.

The conventional approach recommended by the manufacturer is to install electric heat trace along the pipe. Because the owner expects to be away from the building for extended periods during winters while traveling and there is the possibility of extended power outages, the owner considered that approach to be insufficient.

Short of installing a full battery backup, or a system to automatically drain the heat pump, we were unable to suggest an option that would completely eliminate the potential for freeze damage during an extended power outage. Our recommendation to supplement the heat trace was to install a small circulator powered by an uninterrupted power supply that would continuously circulate water between the buffer tank/radiant floor and outdoor unit whenever the pipe temperature dropped below 40F. This would run for as long as the battery has power, and will use the house as a thermal storage reservoir.

However, when the heat pump did experience a failure condition during below freezing temperatures, the circulating pump failed to perform as intended. The most significant factor was likely the flow rate setting for the pump, which was set by the owner. In the interest of extending the battery operation, the owner attempted to set a flow rate in the 0.02 GPM range. Arguably a flow rate closer to the normal operating range of 0.5 GPM would have performed better, but the combination of no heat trace and a flow rate less than 5% normal operation was not sufficient to prevent freezing.

Another contributing factor may have been the final location of the circulator. Under all previous layouts, the freeze protection pump was either coupled with heat trace, as recommended by the manufacturer, or replaced with an inline pump and boiler on the outdoor side of the heat pump to buffer tank loop. With the final mid-installation relocation of the boiler to the indoor side of this loop, the outdoor loop was largely decoupled from the house side of the system. The DC circulator could only provide as much heat as is stored in the buffer tank instead of tapping into the much greater thermal mass of the basement radiant floor slab and house itself.

5.2.4.3 Design Considerations: Known Limitations

The Sanden unit has some fine text limitations on its use as a heating system, including the caveats that:

- Despite a 15 kBtu rated capacity, heating use should be limited to 8 kBtu or lower, and in outdoor conditions that never drop below 27F.
- Heating use is only allowed in combination with use as a domestic hot water source, with at least 25 gallons of domestic hot water use per day.
- Systems used for heating must be installed with a Taco X-Block packaged pumping, heat exchanger and control system.

Additionally, some limitations were discovered that are not called out as concerns in the official documentation:

- Flow rates through the Sanden unit are extremely low (~0.5 GPM), particularly as the supply water temperature approaches its highest setpoint. To effectively deliver the heat provided by the Sanden, the X-Block is moving approximately four times as much water, and is permanently programmed to cycle on at full pump speed before ramping down as needed to maintain a desired temperature drop across the heat exchanger. The effective result is that under most conditions, the water in the buffer tank is quickly circulated through the X-Block heat exchanger and returned, mixing the water in the tank and largely eliminating the temperature differences and stratification needed for optimal operation.
- Although the Sanden is able to produce significantly hotter 170F supply water temperatures than other air-to-water heat pumps, it is still limited by the temperature of return water delivered to the unit. The Sanden unit is designed to cycle off as soon as water over 122F is detected entering the unit. With the above mentioned high circulation rates and mixing, a delicate balance must be achieved that provides hot enough water from the Sanden to effectively condition the served spaces, but is low enough that the return water from the X-Block will stay below 122F until the load has been satisfied. A general estimate would be that supply water setpoints of 140F or under would achieve this, which is similar in performance range to the Solstice system.
- We believe that in the combination heating and domestic hot water configuration, the Sanden units should include an expansion tank. This is not required by the manufacturer, but with the X-Block recirculation as recommended, check valves are required to prevent hot water from flowing back into the cold water supply. These check valves allow makeup water to enter the buffer tank at ground water temperatures (~60F), but prevent any flow back as the water is heated and expands, generating pressure in the tank.

5.3 Riders Mills Road

Figure 10: Riders Mills Road- Elevation Photo

View of the site from the driveway. Site consists of a stand alone garage with no connection to the house envelope, a two story central section, and a single story bedroom section at the rear. The main two story section has a finished basement that extends 2/3 the width of the upper floors, and continues under the single story bedroom section.

5.3.1 Site Description

This site is a two story custom built high efficiency house, with a finished great room adjoining a two story open kitchen and a detached garage. The interior is largely open plan with large windows. Heat is provided via radiant floor zones in the basement, first floor and on the partial second floor. A supplemental ductless split heat pump is located on the second floor.

Table 10: Riders Mills Road – At-a-glance Site Metrics Table

Summary of characteristic features for the Rider Mills Road site.

Building Size:	1,989 SF
Heating Load:	not calculated – system pre-installed
Mechanical System:	The site has a 3-zone radiant floor system. Two of the zones (upper floor and the main floor) are controlled together, while the third (basement) is independently controlled. Within each zone, there are individually adjustable balancing controls for the radiant loops. A supplemental air-to-air heat pump is installed on the second floor, and an instantaneous electric hot water heater provides domestic hot water
Energy Efficiency of the Building:	Condition of Envelope: Insulated (spray foam) new construction, appears to be very tight. Energy efficiency recommendations: None noted
Unique Features and Owner Motivations:	The owner is an HVAC contractor, who installed the system in his home before recommending it to clients. Owner added a solar thermal refrigerant pre-heat system mid-way through the analysis period

5.3.2 Factors for Success

Key factors for success at this site included:

- Invested Owner – interested and committed to exploring this technology.
- Knowledgeable Owner – HVAC professional, secondary goal of project is to provide installation experience.
- New construction site, with radiant floor system well suited to low temperature radiation.

5.3.3 Demonstration Site Evolution

The site was designed and installed by the owner prior to involvement in this study. The owner selected this system for their building as a way to become familiar with the technology before installing units for any clients.

5.3.4 Site Design

This installation features the use of glycol in the entire system, instead of having the glycol isolated to the outdoor components with a heat exchanger. This can be more expensive as a first cost, but provides a secondary freeze protection benefit to the rest of the building, and can result in higher temperature supply water. The site was also somewhat different from a typical residential installation in that some control tasks, such as backup heat, were controlled manually instead of automated.

Partway through the monitoring period, the owner of the Rider Mills site installed a new buffer tank, with a solar thermal assisted pre-heat heat pump element. This system is similar to a second heat pump, but replaces the evaporator with a solar thermal panel. The new unit is provided as a packaged system with a storage tank that is now being used as the air-to-water heat pump system buffer tank.

The owner intends to have this system, which has a limited capacity, pre-heat water in the tank up to a certain point, beyond which the Solstice air-to-water heat pump will take over. The tank has been outfitted with a stainless steel coil that the owner is planning to use to pre-heat his domestic hot water, routing cold domestic water through the coil on its way to his instantaneous hot water heater.

Diagrams and photos of the installed system are included in Appendix A.

5.4 Steuben Valley Road

Figure 11: Steuben Valley Road- Elevation Photo

View of the site from the driveway

5.4.1 Site Description

This demonstration site is a detached office built by the owner specifically around low temperature distribution heat emitters. Previously, an oil fired boiler was the heat source, however the Solstice Extreme unit was installed two years ago and is now used as the primary heating source, with the oil boiler as backup.

Table 11: Steuben Valley Road – At-a-glance Site Metrics Table

Summary of characteristic features for the Steuben Valley site.

Building Size:	1,088 SF
Heating Load:	18,000 Btuh (per Owner) 74,000-120,000 Btu (Oil Boiler Capacity)
Mechanical System:	The building is hydronically heated, with 6 zones. The primary zones consist of radiant floor, wall and ceiling panels (one zone per floor), with additional smaller zones for vertical panel radiators and towel warmers (primarily demonstration use), an indirect fired DHW tank, and other radiant system zones. A wall mounted cooling unit is installed and fed by the buffer tank, with another cooling unit expected in the future. Cooling use is minimal and units used as humidity control system as much as for temperature control. Domestic hot water is produced by the heating system via indirect fired DHW tank or by an instantaneous electric water heater with a manual change over valve (operated by the owner with the operation of the oil boiler).
Energy Efficiency of the Building:	Condition of Envelope: The building envelope is tight and insulated. Walls have 1.5" of spray foam over 3.5" of batt insulation. The ceiling is comprised of 2x8 trusses and has 2" of spray foam and 6" of batt cavity insulation. Energy efficiency recommendations: There are no obvious energy efficiency improvements noted at this site.
Unique Features and Owner Motivations:	The owner is active in the hydronic heating field, and uses his office as a demonstration site for multiple technologies. He has installed a wider array of systems and systems components than most typical homeowners and as a result his system is more complex. In contrast to that, he manually controls change over to the backup heat source and heating/cooling switching instead of implanting an automatic system.

5.4.2 Factors for Success

Key factors for success at this site included:

- Well informed and technically adept owner
- Availability of at-cost parts to the owner

5.4.3 Demonstration Site Evolution

Although the heat pump was installed two years ago, it has only been active for a single winter. The first year it was installed, the owner tried to use it with a smaller, less effective buffer tank/heat exchanger combination that had been used as part of his existing system. The owner reports that the heat pump cycled frequently with this setup, and suspects that the heat exchanger built into the buffer tank had been unable to transfer heat from the heat pump system to the distribution water as quickly as the heat pump was producing it.

The owner has since replaced the buffer tank/heat exchanger system with a separate 5"x12" 100 plate heat exchanger, and an 80 gallon insulated tank. The heat pump was operated with this setup for the 2017-2018 winter season and did not evidence the same short-cycling issues previously noted.

Despite the owner's experience and technical expertise, a number of minor changes were made after the measurement and verification results began to come back, which showed lower than expected efficiency from the system (approximately 0.6 COP less than would be expected for the system at the experienced outdoor conditions per the manufacturer). These included implementing reset controls (complicated by the need to coordinate reset curves for multiple control systems), investigating changes to pumps to allow more flow from the buffer tank into the primary loop, and investigating ways to reduce parasitic energy losses from the pumps, crankcase heater and radiation from the tank when the heat pump was not active.

These continued modifications, after over a year of use, and on the system installed and operated by an owner who is the engineer involved in writing the current application guide for this product, show how difficult it can be to properly configure a system like this.

5.4.4 Site Design

The site was installed and designed by the owner prior to involvement in this study. This installation features the use of a heat exchanger. The site was also somewhat different from a typical residential installation in that some control tasks, such as switching to backup heat, were left to be done manually instead of automated.

Some of the key system elements incorporated at this site include:

- 80 gallon buffer tank and 5"x12" 100 plate heat exchanger – this pair of elements replaced a previous evolution of the system which made use of an indirect hot water tank with integral coil, which had insufficient heat transfer capacity.
- This is the only system that also uses the heat pump for cooling. There is a 1 ton wall mounted cooling unit which is used in the summer and plumbed to the same heat pump and buffer tank, but on its own circulation loop.
- Instead of an automatic backup enabled control, this system uses a manual backup control which the owner reports he engages at roughly -5F.
- This system serves a low temperature hot water distribution system. This allows the owner to achieve suitable comfort levels with a 130F high temperature limit setpoint.
- Unique to this site, there are several different heat emitters and systems served by the primary hydronics. This includes the wall mounted forced air units (heating and cooling); radiant floor, ceiling and wall sections; and other diverse radiation elements such as towel warmers and panel radiators. These are installed largely for demonstration purposes, but also provide significantly more heat distribution capacity than most residential installations.

5.5 Garrett Road

Figure 12: Garrett Road- Elevation Photo

View of the site from the driveway. Attached garage is single story.

5.5.1 Site Description

This demonstration site is a two story residence, with an unfinished basement. The upper floor contains two heating zones serving bedrooms, and the downstairs zone includes kitchen, study, and living room spaces. A wood stove is centrally located in the living room and used to supplement an existing oil boiler located in the basement.

Table 12: Garrett Road – At-a-glance Site Metrics Table

Summary of characteristic features for the Garrett Road site.

Building Size:	1,784 SF
Heating Load:	Air-to-water heat pump heating primarily desired for the kitchen and study (existing load for these spaces calculated at roughly 6,750 Btuh)
Mechanical System:	The building is hydronically heated, with 4 zones, one for the bottom floor, two for the upper floor and one (seldom used) for the basement. Each zone contains a controlling thermostats. Pre-retrofit, the building was heated by an oil fired boiler and woodstove. Additional radiation elements and a section of radiant floor were added to provide supplemental heat output to the kitchen and study. There is a second floor air-to-air heat pump system, used for cooling.
Energy Efficiency of the Building:	Condition of Envelope: Considered to be standard code compliant construction, average air tightness Energy efficiency recommendations: Investigate backdraft dampers for kitchen exhaust, and insulation/air sealing of cantilevered spaces.
Unique Features and Owner Motivations:	The owner is very engaged and technically savvy. He has experience with designing similar systems. The owner expects to continue using the wood stove for heat and does not intend to carry the entire building load with this system.

5.5.2 Factors for Success

Key factors for success at this site included:

- Invested Owner – interested and committed to exploring this technology.
- Knowledgeable Owner – HVAC design professional, knowledgeable about the technology.
- Existing Backup Heat – site has an existing oil boiler and wood stove which are together more than capable of meeting the space loads under peak heating conditions.

5.5.3 Demonstration Site Evolution

This site was the last to be selected and is the only one to also have a wood heat source present. The initial interest by the owner was to supplement the current wood heat in two spaces on the first floor, increasing the heating capacity in those two spaces, while retaining the existing distribution system elsewhere. The oil boiler would be retained as backup and to supplement the heat pump and wood heat.

After installation of the air-to-water heat pump, the owner became interested in increasing the heat delivered to the additional spaces, which had been mainly wood-heated with some level of supplemental heat from the boiler. This required higher supply water temperatures to effectively deliver heat with the current radiation in those spaces, which had not been altered for lower temperature water use. This expansion of the hydronic heating systems role was also triggered by equipment issues with the wood stove, which required reliance on the hydronic heat while the stove was being serviced.

To allow the heat pump to supply higher temperature supply water, the heat exchanger was removed and the entire system filled with a 70% water- 30% propylene glycol mix. The owner reports improved comfort with this alteration.

5.5.4 Site Design

5.5.4.1 Evaluating heating capacity of distribution system at various temperatures

As with the other sites, an analysis of the existing distribution system was performed. For this site, the owner was not interested in modifications to the distribution heating elements in any of the spaces that were maintained at comfortable temperatures by the wood stove. It was understood that reducing the overall temperature in the hydronic system would decrease output to the entire house, but the owner felt that the wood stove would be adequate to supply heat to those spaces while the heat pump was in use.

With that approach, our analysis was limited to two spaces (kitchen and study) outside the wood stove's immediate range that needed additional heat. The heat loss from those spaces and length of active existing baseboard was documented. The equivalent heat output at various average water temperatures was calculated using AHRI steam ratings and Modine performance tables, and the additional heat requirement determined. Copies of these calculations are included in Appendix A.

From these calculations, we provided the amount of additional heat output capacity that would be needed for those spaces. Supplemental heating systems were then selected and installed by the owner, including high capacity radiation and a small section of radiant floor.

5.5.4.2 System Sizing

This system was intended for supplemental use in a specific set of spaces, with the understanding that the existing wood stove would provide the primary heat to maintain the living room and upstairs spaces, and that the existing oil boiler would be available for backup at lower outdoor air temperatures. A full load calculation was not performed and we evaluated the impact of lower average water temperatures on performance in the kitchen and study only. For those spaces, the available unit size was more than adequate and operation range was limited by minimum temperatures needed to deliver heat through the existing system rather than maximum unit capacity.

5.5.4.3 Evaluating Pump and Control Strategies

As part of the design, we selected an outdoor reset controller that would enable the existing boiler and disable the heat pump at an owner specified outdoor air temperature. This was implemented with a relatively inexpensive off the shelf controller and set of relays.

One element of the design for this site that was unique among the sites was the direct tap of the supply water from heat pump before it reached the buffer tank. This is a strategy popularized in geothermal heat pump systems and allows a slightly hotter temperature supply water to be delivered, as well as reduces flow through the buffer tank. We did not observe measurable benefits from the strategy and the direct tap approach was removed at the same time that the heat exchanger was eliminated. Concerns with impacts on the system while the heat pump went through defrost cycles were cited by the owner as the reason for the alteration.

The owner is continuing to refine the switching point to engage the backup boiler system. Part of the evolution is driven by continued optimization. The operating expectations and use of the system are also evolving, leading to exploration of how much of the building load the system can effectively carry, and under what conditions it is cost effective for it to run instead of the oil boiler.

5.5.4.4 Evolving Layout

Because of the re-prioritization to emphasize maximum average water temperature and high flow in the distribution system, the owner elected to remove the heat exchanger in late February of 2019. This allowed for a general increase in supply water temperature.

There have been no noted negative side effects from this revision, and there are reports of less cycling and greater overall comfort. Temperature and performance data from the use periods immediately before and after the heat exchanger replacement are included in Appendix A

Appendix A: Supporting Documents

Design, analysis and other supporting documents for the demonstration sites collected during this project are included in this appendix.

A.1 Sapsucker Woods Road: Supporting Calculations and Field Documents

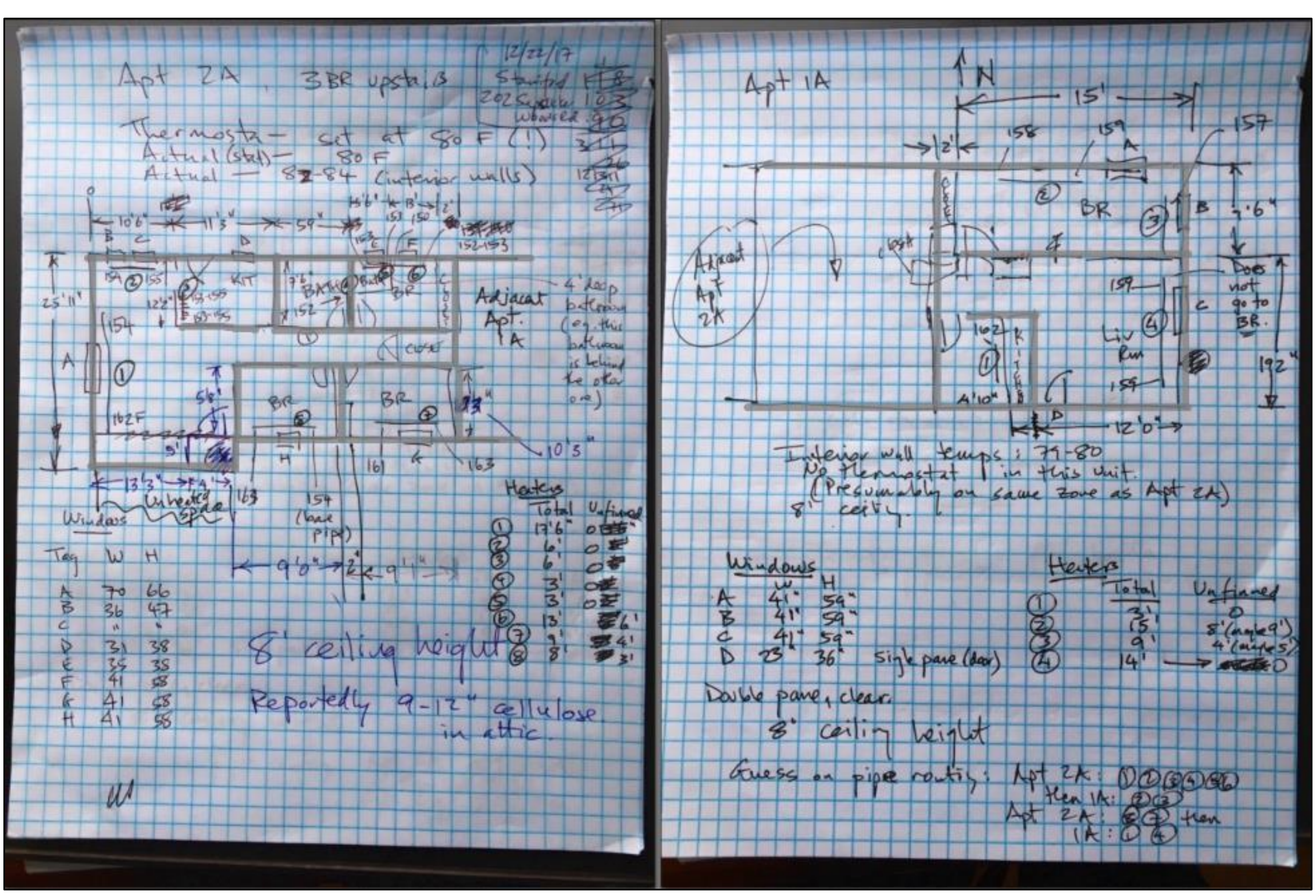
Site Overview Photos

Figure 13: Sapsucker Woods Road- Elevation Photo

View of the site from the driveway. Upper and lower entrances visible, garage and near side windows (note larger upper story windows).

Figure 14: Sapsucker Woods Road- Floor Plan

Rough floor plan of the top story (lower story similar). From project field notes, 12/22/17.



Installation Photos

Figure 15: Sapsucker Woods Road - Outdoor Unit

Solstice Extreme Heat Pump unit installed outside at the Sapsucker Woods Road site. 4/9/2018

Figure 16: Sapsucker Woods Road - Buffer Tank

Buffer tank installed in insulated closet at the Sapsucker Woods Road site. 4/23/2018

Design Documents

Figure 17: Sapsucker Woods Road - Pipe Schematic and Sequences

Design control sequence and pipe layout provided to the owner and installer for the Sapsucker Woods Road site

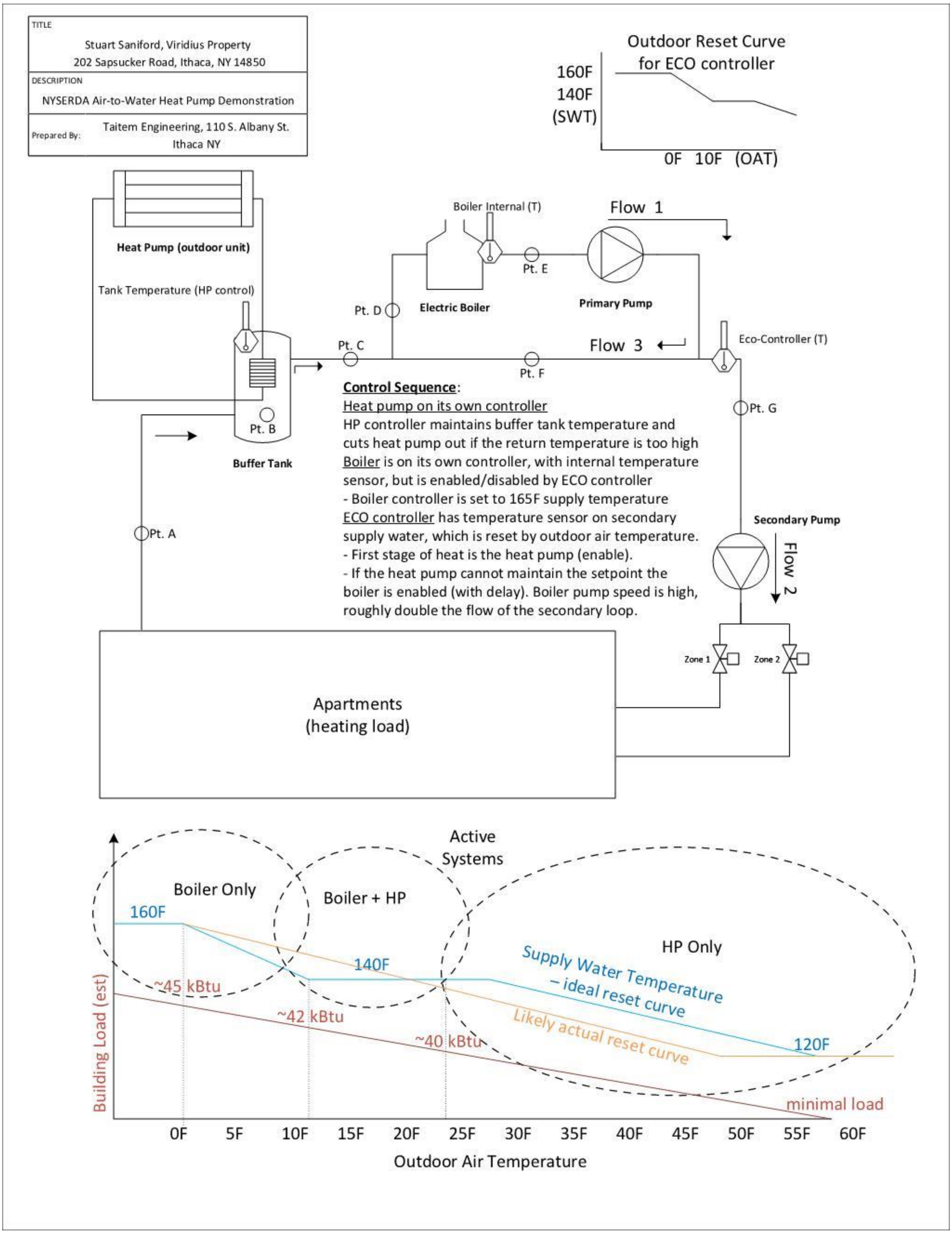


Figure 18: Sapsucker Woods Road - Distribution Capacity and Temperature Calculations

Spreadsheet calculation, with reference tables, used to calculate existing distribution system capacity at various average water temperatures, and flow rates.

202 sapsucker woods road — **PER MEASURED BASEBOARD**

Source: file:///C:/Users/NateT550/Downloads/12-135.4_Catalog,_Commercial_Fin_Tube_Radiation.pdf

2nd 3br apt- approx. 10dt

Dimensions
79.5 ft (finned) 3br+1br
28 ft (unfinned)

perimeter finned (equivalent? Have to add in a factor for unfinned)
80.9 feet 0.05 correction factor for unfinned
* based on rough numbers from
on both floors https://forum.heatinghelp.com/discussion/72939/heat-loss-of-bare-pipe-johnny
161.8 feet

Assuming baseboard equal on both floors
161.8 lf

fin tube correction factor (160 EWT, 140 LWT) --CORRECTION, dT actually ~10F
0.51 correction for average temp of 160/155F

Btuh/LF
similar unit(at STP, AHRI)
840

Existing capacity (baseboard)	**Existing Boiler**	new electric boiler
69,315 Btuh	83,000 Btu	54,590 Btu

Estimated building load at 38F
30,000 Btu

Estimated load at 0F (per rough discussions and numbers with Ian)
60,000 Btu (should be under this)

Proposed capacity

drop speed (3/4" copper from ~5 gpm to ~1 gpm)
0.931 correction factor (rough)

--> need to get return water temperatures below 130 (preferably 120)

heat pump--> 120 to 140
AWT = 130

new distribution capacity
0.33 correction factor

corrected for lf of existing, slower speed
41,756 Btuh

Table 10.1 - Converting AHRI Steam Ratings to Hot Water Ratings at Indicated Temperature ①

Average Water Temperature	Factor	Average Water Temperature	Factor
100	0.15	185	0.73
110	0.20	190	0.78
120	0.26	195	0.82
130	0.33	200	0.86
140	0.40	205	0.91
150	0.45	210	0.95
155	0.49	215	1.00
160	0.53	220	1.05
165	0.57	225	1.09
170	0.61	230	1.14
175	0.65	235	1.20
180	0.69	240	1.25

① Multiply correction factor x 1 PSI steam rating to determine Btu at actual water temperature rating.

MODEL SP PERFORMANCE MODINE

Table 13.1 - Steam and Hot Water Ratings - Fin Size - 3-1/4" x 2-3/4"

FIN SIZE - 3-1/4" X 2-3/4" ALUMINUM												
Heating Element Fin Spacing	Enclosure Height (Inches)	Rows of Element	1 PSI Steam	Hot Water Ratings - BTU/HR/FT - AWT °F								
				210	200	190	180	170	160	150	140
3/4" Copper 34 Fins/ft.	8	1	840	800	720	660	580	510	450	380	340
	10	1	860	820	740	670	590	520	460	390	340
	14	1	910	860	780	710	630	560	480	410	360
	14	2 @ 5"	1420	1350	1220	1110	980	870	750	640	570
3/4" Copper 42 Fins/ft.	8	1	910	860	780	710	630	560	480	410	360
	10	1	950	900	820	740	660	580	500	430	380
	14	1	1040	990	890	810	720	630	550	470	420
	14	2 @ 5"	1480	1410	1270	1150	1020	900	780	670	590
3/4" Copper 50 Fins/ft.	8	1	980	930	840	760	680	600	520	440	390
	10	1	1040	990	890	810	720	630	550	470	420
	14	1	1160	1100	1000	900	800	710	610	520	460
	14	2 @ 5"	1540	1460	1320	1200	1060	940	820	690	620
1" Copper 34 Fins/ft.	8	1	820	780	710	640	570	500	430	370	330
	10	1	850	810	730	660	590	520	450	380	340
	14	1	900	860	770	700	620	550	480	410	360
	14	2 @ 5"	1370	1300	1180	1070	950	840	730	620	550
1" Copper 42 Fins/ft.	8	1	880	840	760	690	610	540	470	400	350
	10	1	930	880	800	730	640	570	490	420	370
	14	1	1020	970	880	800	700	620	540	460	410
	14	2 @ 5"	1410	1340	1210	1100	970	860	750	630	560
1" Copper 50 Fins/ft.	8	1	940	890	810	730	650	570	500	420	380
	10	1	1010	960	870	790	700	620	540	450	400
	14	1	1130	1070	970	880	780	690	600	510	450
	14	2 @ 5"	1450	1380	1250	1130	1000	880	770	650	580
1-1/4" Copper 34 Fins/ft.	8	1	810	770	700	630	560	490	430	360	320
	10	1	840	800	720	660	580	510	450	380	340
	14	1	890	850	770	690	610	540	470	400	360
	14	2 @ 5"	1310	1240	1130	1020	900	800	690	590	520
1-1/4" Copper 42 Fins/ft.	8	1	860	820	740	670	590	520	460	390	340
	10	1	910	860	780	710	630	560	480	410	360
	14	1	1000	950	860	780	690	610	530	450	400
	14	2 @ 5"	1340	1270	1150	1050	920	820	710	600	540
1-1/4" Copper 50 Fins/ft.	8	1	910	860	780	710	630	560	480	410	360
	10	1	980	930	840	760	680	600	520	440	390
	14	1	1110	1050	950	870	770	680	590	500	440
	14	2 @ 5"	1360	1290	1170	1060	940	830	720	610	540

Table 11.2 - Factors for Reduced G.P.M. and Velocity ①

Ft./Sec. Velocity	Gallons Per Minute — Copper			Correction Factor
	3/4" Dia.	1" Dia.	1-1/4" Dia.	
3.0	5.0	8.5	12.9	1.000
2.5	4.2	7.1	10.7	0.992
2.0	3.3	5.7	8.6	0.984
1.5	2.5	4.2	6.4	0.973
1.0	1.7	2.8	4.3	0.957
0.5	0.8	1.4	2.1	0.931
0.25	0.4	0.7	1.1	0.905

① The factors in this table may be used only when the water flow rate through the finned tube unit is known and where the flow rate is less than three feet per second. To determine the output at less than three feet per second, multiply the AHRI Water Rating by the factor in this table which applies to the known flow rate.

Figure 19: Sapsucker Woods Road - HAP Engineering Model Simulation Results

Engineering model results predicting building heating load, created using HAP

Monthly Simulation Results for FTR System

Project Name: sapsucker woods 2.0
Prepared by: Taitem

04/19/2018
04:03PM

Air System Simulation Results (Table 1) :

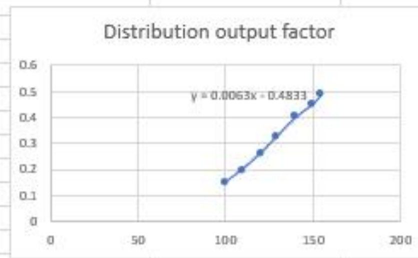
Month	Terminal Heating Coil Load (kBTU)	Terminal Fan (kWh)	Lighting (kWh)	Electric Equipment (kWh)
January	17058	0	123	179
February	15101	0	111	161
March	11346	0	123	179
April	5863	0	119	173
May	1063	0	123	179
June	0	0	119	173
July	0	0	123	179
August	0	0	123	179
September	454	0	119	173
October	4651	0	123	179
November	9688	0	119	173
December	16236	0	123	179
Total	**81460**	**0**	**1445**	**2102**

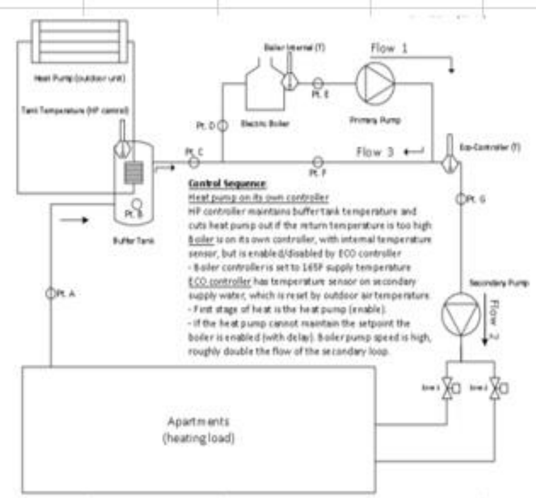
Figure 20: Sapsucker Woods Road - Loop Temperatures at Various Loads

Spreadsheet calculations created to predict loop water temperatures, building heat delivered, supply water setpoint and loop flowrates.

SAPSUCKER WOODS ROAD

Constants		
Distribution: equivalent l	161.8	
Btuh/LF (STP, AHRI)	840	
Corr. Factors (AWT)		
at 100F	100	0.15
at 110F	110	0.2
at 120F	120	0.26
at 130F	130	0.33
at 140F	140	0.4
at 150F	150	0.45
at 155F	155	0.49
Boiler Capacity		
54590		





Flow2*Tc+Flow3*Tf=Flow1*Td
flow3=flow1-flow2
Flow2*Tc+(flow1-flow2)* Tf = Flow1* Td
Td =(Flow2*Tc+(flow1-flow2)* Tf)/ Flow1

Qb=Qload-Qhp
Qb= flow1*500*(Te- Td)
Flow1 =Qb/(500*(Te- Td))
Flow1 =Qb/(500*(Te-((Flow2*Tc +(flow1- flow2)*Tf)/Flow1)))
(expanded on paper)
Flow1=((Qload-Qhp)/500+Flow2*(Tc-Tf))/(Te-Tf)

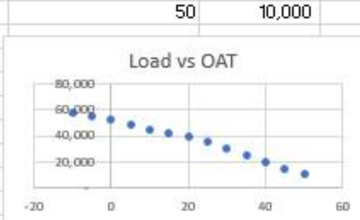
flow 1*Te-flow3*Tf=Flow2*Tg
flow3=flow1-flow2
flow1*Te-(flow1-flow2)* Tf =Flow2*Tg
flow1*(Te-Tf)=Flow2*(Tg-Tf)

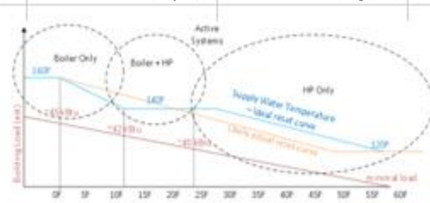
(Qload-Qhp)/500+Flow2(Tc-Tf)=Flow2*(Tg-Tf)
(Qload-Qhp)/500=Flow2(Tg-Tc)
--> Tf and flow 1/3 are imaterial if boiler heat output controlled... if flow 1 is greater than flow 2, Tf=Te, else Tf=Tc
--> if we want Tg to be variable we need to have flow 1 less than flow 2. BUT flow 1 must be high enough to run boiler, and to handle full heat load at design temp

Selected 2ndary flow 5.2 gpm — suggest 5.2, may have a slightly greater than 20F dT, right before HP kicks off

Selected primary flow 4.4 gpm — Rate that delivers full boiler output

Outside Air Temperature [F]	Building Load [Btuh] (guess)	Return T [a] <=130F [F] for HP --> temperatures selected based on required dist.	Dist. Capacity (est. 10F dT) [Btuh] >= bld load	**Dist. Capacity (est. 20F dT) [Btuh] >= bld load**	Dist. Capacity (est. 30F dT) [Btuh] >= bld load	Supply SP [g] [F]	2nd Flow **[flow 2]** [gpm] (Q=gpm*500*dT)	Heat Pump capacity [Btuh] f(T) (guess)	tank output [c] [F] dT(c-a)=Q/gpm*500	Boiler Supply [e] [160 F]	**Flow1** [gpm] assume greater than flow2. Tf=Te	**Flow1** [gpm] assume flow1 less than flow2, Tf=Tc	Boiler output capacity (fast flow) Q=500*gpm*dT	(slow flow) Q=500*gpm*dT	capacity at variable flow (cycling)	Run cycle (% boiler)
-10	58,000	135	54,188	**58,469**	62,751	155	**5.8**	5,000	135	160	div by 0 issue	4.4		55,000	54,590	99%
-5	55,000	130	49,907	**54,188**	58,469	150	5.5	15,000	136	160		3.2		53,308	39,188	74%
0	52,000	130	49,907	**54,188**	58,469	150	5.2	20,000	138	160		3.1		49,077	34,188	70%
5	48,000	125	45,626	**49,907**	54,188	145	4.8	30,000	137	160		1.7		51,615	19,907	40%
10	45,000	120	41,344	**45,626**	49,907	140	4.5	35,000	133	160		0.8		58,385	10,626	23%
15	42,000	120	41,344	**45,626**	49,907	140	4.2	40,000	135	160		0.5		54,154	5,626	12%
20	39,000	120	41,344	**45,626**	49,907	140	3.9	45,000	137	160		0.1		49,923	626	1%
25	35,000	120	41,344	**45,626**	49,907	140	3.5	48,000	138	160		0.0		47,385	-	0%
30	30,000	110	32,782	**37,063**	41,344	130	3	48,000	128	160		0.0		69,385	-	0%
35	25,000	110	32,782	**37,063**	41,344	130	2.5	48,000	128	160		0.0		69,385	-	0%
40	20,000	100	24,220	**28,501**	32,782	120	2	48,000	118	160		0.0		91,385	-	0%
45	15,000	100	24,220	**28,501**	32,782	120	1.5	48,000	118	160		0.0		91,385	-	0%
50	10,000	100	24,220	**28,501**	32,782	120	1	48,000	118	160		0.0		91,385	-	0%





heat pump function: requires 12 gpm minimum, 10dT
Q=gpm*500*dT
60000 some loss through heat exchanger?

9.2

Figure 21: Sapsucker Woods Road – Controls Setpoint Change Log

Spreadsheet containing record of control setpoints starting with defaults and tracking changes made over the course of each visit. The changes from default settings are shown in yellow, with darker fill and bold entries indicating each period that a change from the previous setting occurred.

Equipment settings for 202 Sapsucker Woods Rd.

Carel µC2 (Solstice Heat Pump)

UOM=Unit Of Measure

Display	Parameter and description	Min	Max	UOM	Default	Custom Setting	Description	Password	SETTING Default	Init. 5/28/18	Rev1 1/5/19	Rev2 2/2/19
Alarm Settings - A -												
A01	Freeze protection temperature	A07	A04	deg	32.0	22	Warning on, compressor turns off if cooling (including defrost), Turns on unit in heating if	22	32.0	32.0	32.0	**22**
A02	Freeze protection differential	0.3	122	deg	4.0		Warning and unit off at A01+A02	22	4.0	4.0	4.0	4.0
A03	Time delay to initiate freeze protect.	0	150	sec	60			22	0	0	0	**60**
A04	Antifreeze heater setpoint	A01	r16	deg	34.0	25	Turns on the circulator and electric heat, if present, below this point in standby, if A10=01 or 02	22	34.0	34.0	34.0	**25**
A05	Antifreeze heater differential	0.3	50	deg	4.0		Turns off the circulator and heater at A04+A05	22	4.0	4.0	4.0	4.0
A06	Antifreeze Probe				00		analog input for freeze protection	66	01	01	01	**00**
A07	Minimum antifreeze setpoint	-40	176	deg	32.0	20	Lowest allowable setpoint for A01	66	32.0	32.0	32.0	**20**
A08	Auxiliary heat	A01	r15	deg	90.0	40	Turns on electric heat, if present, in Heating or Defrost below this point	22	90.0	90.0	90.0	**40**
A09	Auxiliary heat differential	0.3	50	deg	5.0		Turns off the heater at A08+A09	22	5.0	5.0	5.0	5.0
A10	Auxiliary heat operation	0	3		02		Turns on the circulator and electric heat, if present, if water temp falls below A01. If A10=2, turns on LAHP in heating mode.	22	01	01	01	**02**
Compressor and Pump Control Parameters - c -												
c01	Min. compr. ON time	0	999	sec	120	300	Compressor, when started, must stay on for this tin	22	120	300	300	
c02	Min. compr. OFF time			sec	120	300		22	120			**300**
c06	Delay at start-up	0	999	sec	0	0	Delay after power-on/call to start compressor	22	0	0	0	0
c07	Delay in turning on compressor after turning on pump	0	150	sec	45	30	Allows circulation of water/glycol so that controller is reading conditioned space conditons,	22	45	**30**	30	30
Protective Circuit Parameters - P -												
P01	Flow switch alarm at startup	0	150	sec	30	15	No-flow condition is ignored for P01 at startup, to allow for circulator to establish full flow without nuisance alarms	22	30	**15**	15	15
P16	High temperature alarm set	-40	176	deg	145	145	Sends High Temperature alarm if returning water temperature exceeds this value	22	145	145	145	145
Control/Regulation Settings - r -												
r03	Heating set point	r15	r16	deg	120	134	Nominal target temperature of delivered water in heating mode	00	120			**134**
r04	Heating differential	0.3	50	deg	8.0	6		00	8.0			**6**
r18	Max temp offset from setpoint	0.3	20	deg	8.0	20	Max deviation from setpoint that can be achieved by outdoor reset	22	8.0	**20**	20	20
r20	Start compensation temp in heating mode	-40	176	deg	30.0	40.0	Ambient temperature below which compensation begins in heating mode	22	30.0	**40.0**	40.0	40.0
r31	Heating compensation constant	-5.0	5.0	deg/deg	0.0	0	Slope of outdoor reset curve, deg water temp/deg ambient temp, heating mode	22	0.0	**-1.0**	-1.0	**0**

HBX-ECO-0550 Geothermal (Reset) Control

	Min	Max	UOM	Default	Custom Setting	Note	SETTING Default	Init. 5/28/18	Rev1 1/5/19	Rev2 2/2/19
1) Heat Pumps										
1) HP Stages	1	3		1	2	1st Stage is Solstice Heat Pump	1	**2**	2	2
2) Lag Time	1	240	min	3	15	2nd Stage is lower temp setting on Argo Boiler	3	**5**	5	**15**
3) Rotate Time	1	99	hour	Off	Off	Min. time between 1st and 2nd stage	Off	Off	Off	Off
4) Rotate Cycles	1	240		Off	Off		Off	Off	Off	Off
5) Off Staging	Off	On		On	On		On	On	On	On
	Min	**Max**	**UOM**	**Default**	**Setting**	**Note**				
2) Tanks: 1) Hot Tank (With Outdoor Reset)										
1) WWSD	35	119	deg	Off	65		Off	**65**	65	65
2) Outdoor Temperature	-40	120	deg	Off	0		Off	**5**	5	**0**
3) Hot Tank Differential	2	100	deg	6	8	These 3 settings apply to the Supply water temp. to the building (not the buffer tank temp.)	6	**8**	**9**	**8**
4) Minimum Tank Temperature	50	200	deg	80	85		80	**90**	90	**85**
5) Maximum Tank Temperature	50	200	deg	115	160		115	**165**	165	**160**
	Min	**Max**	**UOM**	**Default**	**Setting**	**Note**				
3) Backup (Backup Stage is the higher (DHW) temp. setting on the Argo Boiler)										
1) Backup Time	1	240	min	Off	10	Min. time between 2nd stage and backup stage	Off	**5**	5	**10**
2) Backup Temperature	2	100	deg	Off	5	Backup stage is locked out above this outdoor	Off	**5**	5	5
3) Backup Differential	2	100	deg	Off	Off	Turns Backup stage on when supply temp falls below this differential	Off	**10**	10	**Off**

Argo AT Electric Boiler

		Min	Max	UOM	Default	Custom Setting	Note	SETTING Default	Init. 5/28/18	Rev1 1/5/19	Rev2 2/2/19
User Settings											
CHS	Comfort Heat Setting	90	180	deg	150	150	lower temp setting	150	150	150	150
dHS	Domestic HW Setting	90	180	deg	170	165	higher temp setting	170	**165**	165	165
dFS	Differential Setting	4	20	deg	10	10		10	10	10	10

A.2 Firetower Road: Supporting Calculations and Field Documents

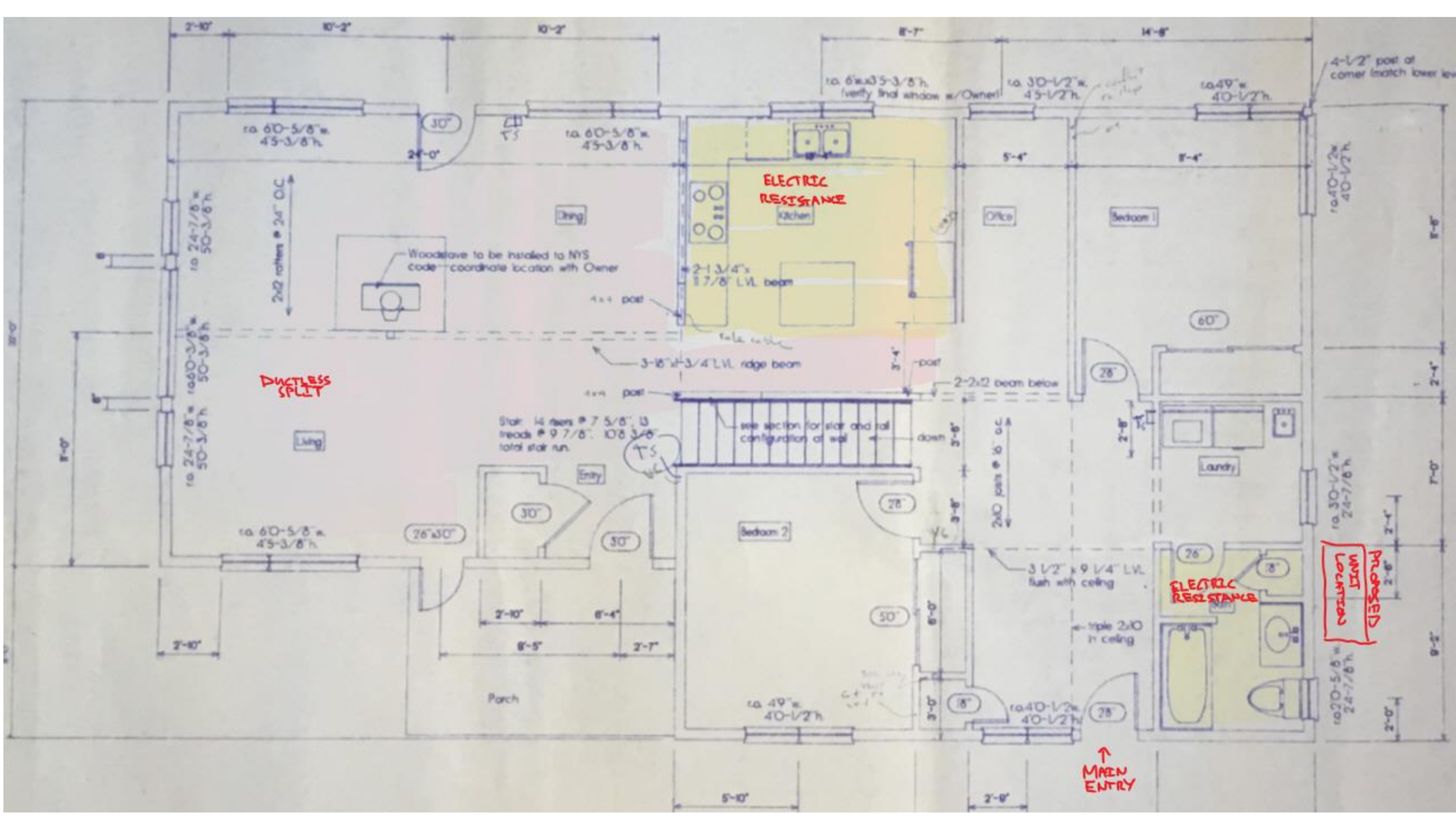
Site Overview Photos

Figure 22: Firetower Road- Elevation Photo

View of the North-West elevation. All three stories visible: site built into slope, basement only fully exposed along North side

Figure 23: Firetower Road - Floor Plan

Floor plan of the main story (floor plans vary between floors). From project field notes, 6/14/17



Installation Photos

Figure 24: Firetower Road - Outdoor Unit

Sanden Heat Pump unit installed outside at the Firetower Road site. 11/30/2018

Figure 25: Firetower Road - Buffer Tank

Buffer tank installed in basement at the Firetower Road site. 11/30/2018

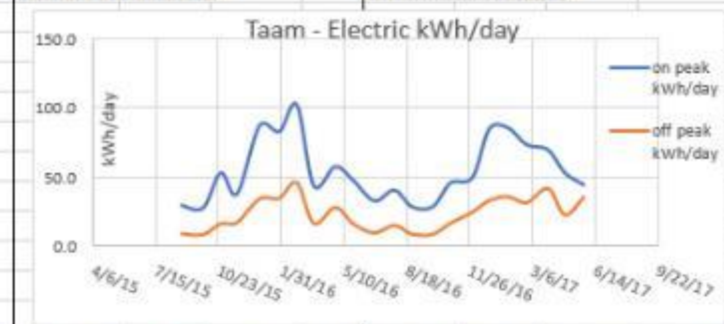
Design Documents

Figure 26: Firetower Road – Utility Analysis

Spreadsheet calculation, with reference utility data, used to calculate range of heating needs for site

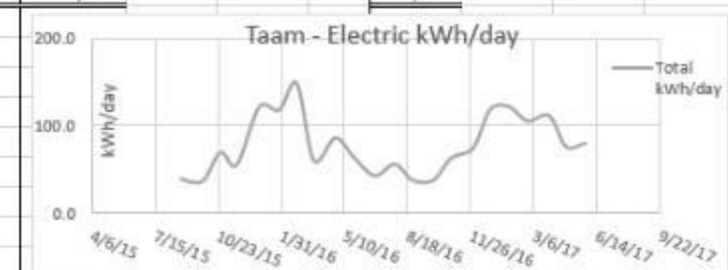
Read Date	Read Type	kwh on	kwh off	Total	Total Tax	total kWh			on peak kWh/day	off peak kWh/day	Total kWh/day
5/26/17	NYSEG	1336	1082	$207.33	$8.53	2418		5/26/17	44.5	36.1	80.6
4/26/17	Estimated	1438	627	$193.19	$7.96	2065		4/26/17	53.3	23.2	76.5
3/30/17	NYSEG	2383	1439	$316.21	$12.64	3822		3/30/17	70.1	42.3	112.4
2/24/17	Estimated	2142	930	$269.20	$10.72	3072		2/24/17	73.9	32.1	105.9
1/26/17	Estimated	2579	1092	$333.17	$13.27	3671		1/26/17	86.0	36.4	122.4
12/27/16		2312	913	$296.40	$11.97	3225		12/27/16	85.6	33.8	119.4
11/30/16	NYSEG	1750	883	$256.95	$10.28	2633		11/30/16	50.0	25.2	75.2
10/26/16	Estimated	1286	485	$183.97	$7.26	1771		10/26/16	45.9	17.3	63.3
9/28/16	Estimated	945	310	$130.21	$5.21	1255		9/28/16	28.6	9.4	38.0
8/26/16	Estimated	802	263	$111.16	$4.48	1065		8/26/16	28.6	9.4	38.0
7/29/16	NYSEG	1306	505	$186.63	$7.32	1811	annual total	7/29/16	40.8	15.8	56.6
6/27/16		1085	340	$139.60	$5.61	1425	28,233	6/27/16	32.9	10.3	43.2
5/25/16	NYSEG	1384	488	$212.52	$8.21	1872		5/25/16	47.7	16.8	64.6
4/26/16	Estimated	1971	976	$302.24	$12.08	2947		4/26/16	58.0	28.7	86.7
3/23/16	NYSEG	1184	459	$149.44	$6.00	1643		3/23/16	43.9	17.0	60.9
2/25/16	Estimated	2879	1304	$367.25	$14.00	4183		2/25/16	102.8	46.6	149.4
1/28/16	NYSEG	2583	1090	$305.41	$11.64	3673		1/28/16	83.3	35.2	118.5
12/28/15		3165	1258	$406.34	$15.64	4423		12/28/15	87.9	34.9	122.9
11/22/15	NYSEG	990	462	$153.10	$5.89	1452		11/22/15	38.1	17.8	55.8
10/27/15	Estimated	1490	474	$172.76	$6.94	1964		10/27/15	53.2	16.9	70.1
9/29/15	NYSEG	942	310	$141.09	$5.41	1252		9/29/15	27.7	9.1	36.8
8/26/15	Estimated	862	282	$124.23	$4.77	1144	annual total	8/26/15	29.7	9.7	39.4
7/28/15	NYSEG	918	284	$137.10	$5.28	1202	27,180	7/28/15			
									on peak kWh/day	off peak kWh/day	
			Totals	########	$201.11	53,988					
				Total	$5,296.61	0.10	average $/kWh	Max	102.8	46.6	
								Min	27.7	9.1	<-- baseload

Estimation technique 1



Estimation technique 2

Heating Load (annual load - baseload1)		Heating Load (annual load - baseload2)	
14,792	kWh	9,983	kWh



Heating Load (annual load - baseload1)		Heating Load (annual load - baseload2)	
13,739	kWh	8,930	kWh
kWh/day		kWh/day	
36.8	Baseload/day	50	estimated baseload/day from chart
13,441	annual baseload1 (kWh)	18,250	annual baseload2 (kWh)

Baseload (average over periods and estimation techniques)

15,845 kWh/year

Heating Load (average over periods and estimation techniques)

11,861 kWh/year

Energy Savings

90%	portion of the heating load covered by heat pump
2.5	COP (heat pump)
$ 0.10	Electric cost per kWh
1,186	Existing electric use kWh (remainder of heating load)
4,270	HP electric use kWh
5,456	Total heating use (kWh/year)
21,301	New total electric use (kWh/yr)
27,707	Previous electric use (kWh/yr)
6,405	Electric heating savings (kWh/yr)
$ 628.38	**$ heating savings ($/yr)**
$ 14,975	**cost after incentives**
23.8	**Simple Payback (years)**

Figure 27: Firetower Road – HAP load calculations

HAP results and analysis used to determine impact of new heat pump on load and utility use

Monthly Simulation Results for Sample Plant

Taam - draft v1
Taitem

12/07/2017
10:45AM

Plant Simulation Results (Table 1):

Month	Heating Coil Load (kBTU)	Plant Heating Load (kBTU)	Heat Pump Output (kBTU)	Remote Hot Water Load (kBTU)	Heat Pump Input (kWh)	Primary Water Dist. Pump (kWh)
January	14217	14217	13088	1129	1309	0
February	12726	12726	10545	2182	1054	0
March	11026	11026	10451	574	1045	0
April	7342	7342	7342	0	734	0
May	3182	3182	3182	0	318	0
June	472	472	472	0	47	0
July	178	178	178	0	18	0
August	348	348	348	0	35	0
September	1929	1929	1929	0	193	0
October	5927	5927	5927	0	593	0
November	9207	9207	9207	0	921	0
December	13639	13639	12734	905	1273	0
Total	**80193**	**80193**	**75403**	**4790**	**7540**	**0**

Monthly Simulation Results for Boiler Plant(1)

Taam - draft v1
Taitem

12/07/2017
01:41PM

Plant Simulation Results (Table 1):

Month	Heating Coil Load (kBTU)	Plant Heating Load (kBTU)	Boiler Output (kBTU)	Boiler Input - Electric (kWh)	Boiler Misc. Electric (kWh)	Primary Water Dist. Pump (kWh)
January	14217	14217	14217	4167	0	0
February	12726	12726	12726	3730	0	0
March	11026	11026	11026	3231	0	0
April	7342	7342	7342	2152	0	0
May	3182	3182	3182	932	0	0
June	472	472	472	138	0	0
July	178	178	178	52	0	0
August	348	348	348	102	0	0
September	1929	1929	1929	565	0	0
October	5927	5927	5927	1737	0	0
November	9207	9207	9207	2698	0	0
December	13639	13639	13639	3997	0	0
Total	**80193**	**80193**	**80193**	**23582**	**0**	**0**

Boiler current use:	36,201	(kBtu)	10,610	(kWh)
Building use (bills)				
--> baseline	15,845	(kWh)		
--> heating	11,861	(kWh)		
Proposed backup use	2909	(kBtu)	2909* 10610/36201= **852.5867**	(kWh)
Proposed HP output	33292	(kBtu)	33292* 10610/36201= **9757.4133**	(kWh)
Proposed HP input (COP 2.5)	9757.5/ 2.5= **3903**	(kWh)		
Proposed total use	852.6+ 3903= **4755.6**	(kWh)		
Upper story use (unchanged)	11861-1 0610= 1251	(kWh)		
Electric savings	10610-4 755.6= **5854.4**	(kWh)	5854.4*.1= **585.4400**	Annual $ savings

Percentage upstairs to downstairs:
10610/11861=0.8945

Note: the upper floors are mostly heat pumps, so COP 2.5 (per Ian direction on GTI), that turns into second floor heat load at about 20-25% of first floor.

That works out very well with Ians studies of upper/lower story heating...

Distribution of heat load (upstairs/downstairs)

- Ratio of upstairs to downstairs (70-90% range) when both stories are kept at same temperature with ind. Temperature control
- Goes to 100% if you turn off upstairs heat and accept 6-10F dT down to up

Screen clipping taken: 12/7/2017 1:37 PM

Figure 28: Firetower Road – Buffer Tank Thermal Storage Calculations

Spreadsheet calculation, with reference documents, used to calculate thermal storage capacity available from the buffer tank

Energy Stored in Tank

E(Btu) = 1 Btu/lbmF *T(f) * Capacity (gal) *8.3 lb/gallon)

	for 1 sanden		
Tank Volume:	89	gal	
Tank Temperature	130	F	(average for entire tank - maximum possible assuming perfect stratification and matched pump flows would be 145F - actual operating highly dependant on pump flow rates)
Tank Energy	96031	Btu	

Change in tank energy to 110 F

Tank Volume:	89	gal	
Tank Temperature	110	F	<-- Unit starts to operate when tank temperature drops below 113F, shuts off when return water to the unit reaches 122F
			<-- Milt reports that he is able to run his system with return water as low as 80F - 110 is a reasonable average temp.
Tank Energy	81257	Btu	
Difference:			
14.77	**kBtu**		System sized for 15 kBtu
			3 kW electric backup is roughly 1/3 of capacity

Concrete floor

https://www.engineeringtoolbox.com/specific-heat-solids-d_154.html

Specific heat of concrete is

0.23

https://www.engineeringtoolbox.com/sensible-heat-storage-d_1217.html

Concrete density

144 lb/ft3

$q = V \rho c_p dt$

Slab details:

1,428 (calculated area)

4 inches (reported thickness from energy audit)

476 Volume (CF)

Energy for a 1F temperature change in the slab

dt = 1 F

15765 Btu

Reference Materials

Unit Operation

As hot water is drawn from the top of the tank for showers etc., cold water enters the bottom of the tank from the city or well cold water supply feed.

The incoming cold water and stored hot water do not fully mix inside the tank (unlike other water heaters), this helps maintain a higher average tank temperature and is called stratification.

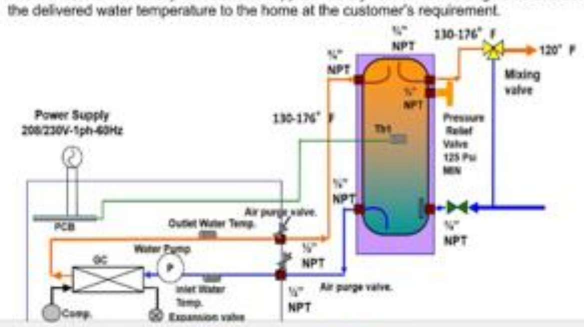
As more hot water is drawn from the tank, the volume of cold water increases, however the tank still remains stratified. When the tank temperature sensor measures the water temperature below 113°F, the heat pump control will start the unit.

The variable speed pump pulls the cold water into the heat pump, and using the heat from the ambient air the water is heated to the user selected water temperature set-point and the returned to the top of the tank.

Heating continues until the water entering the heat pump heat exchanger is 122°F, at which point the heat pump will cycle off and the tank is now completely full of hot water.

The $SANCO_2$ unit will produce hot water at temperatures between 130°F and 176°F depending on set-point chosen.

Therefore, it is mandatory to install the supplied Honeywell AM101 mixing valve and set the delivered water temperature to the home at the customer's requirement.



This is from Sanden regarding capacity, flow and temperatures for the unit (with some calculated mark ups on dT that I did):

- Sanden units are weird
- The colder the water sent to the Heat Pump the higher our Capacity & Efficiency!!!

Inlet Water Temp °F	Unit Capacity (kw) / Btu/h	Unit COP	Flow Rate (GPM)	Calculated dT
50	4.5 / 15,400	4.5	0.32	96.25F
80	3.4 / 11,600	3.3	0.38	61F
100	3.0 / 10, 200	2.7	0.45	45.3F
115	2.6 / 8,900	2.4	0.49	36.3F
120	2.4 / 8,100	2.0	0.58	27.9F

Gen2 Data – Gen3 Product is + 5% in efficiency

Sanden units are weird → direct quote from the manufacturer included on this slide

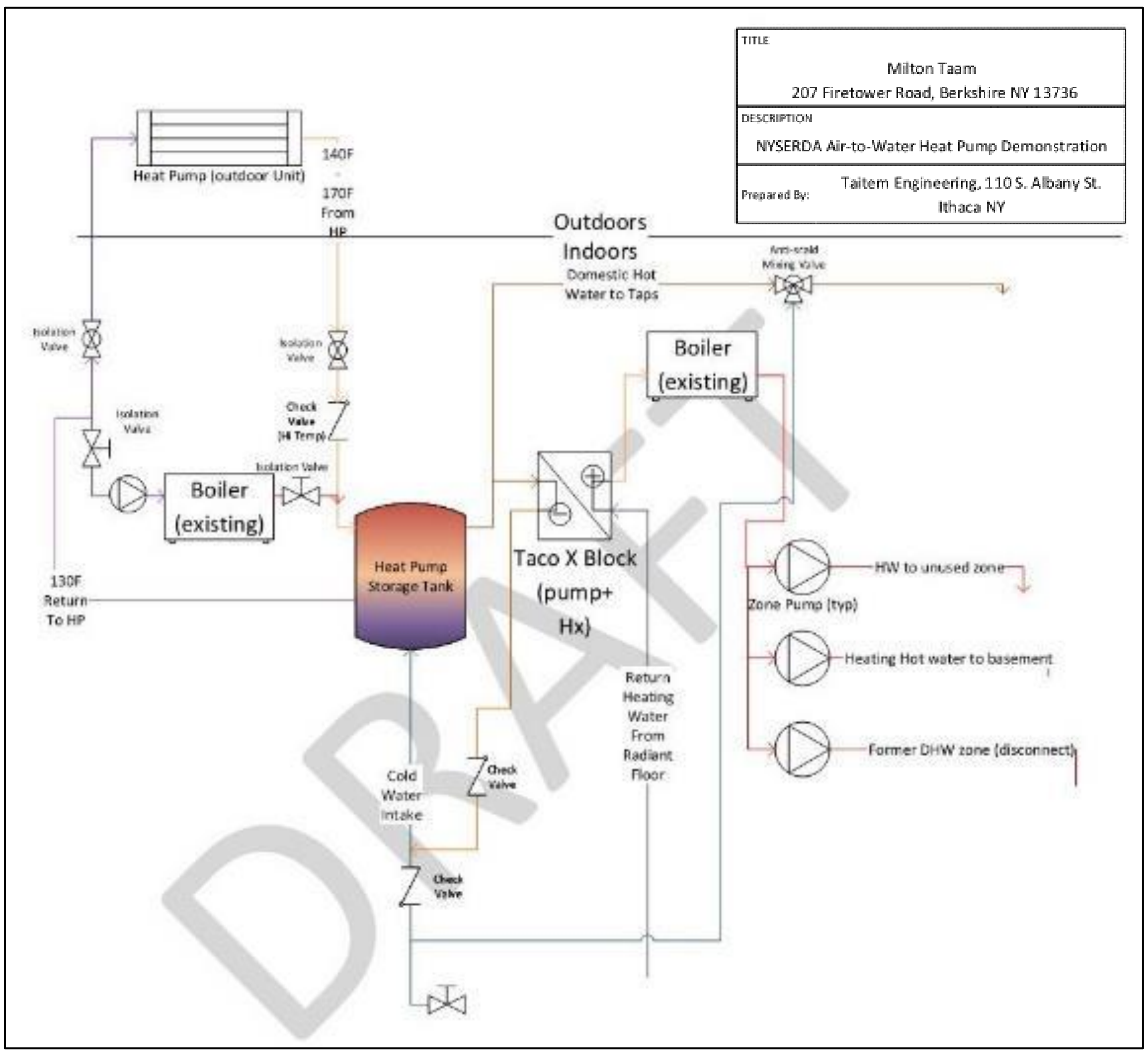
Note that the unit is able to deliver more heat at lower inlet temperatures, but at lower flow rates the dT is insane - 150F output water at 50F inlet, etc.

Without doing any calculations, I would say that we need to match the flow through the Hx to be less than or equal to the flow through the HP to keep the tank from getting drained too quickly. Since that flow is directly tied to the dT - we need to ensure the return water from the radiant floor zones is low enough. I would guess that it is not right now, and we need to be throttling the the flow.

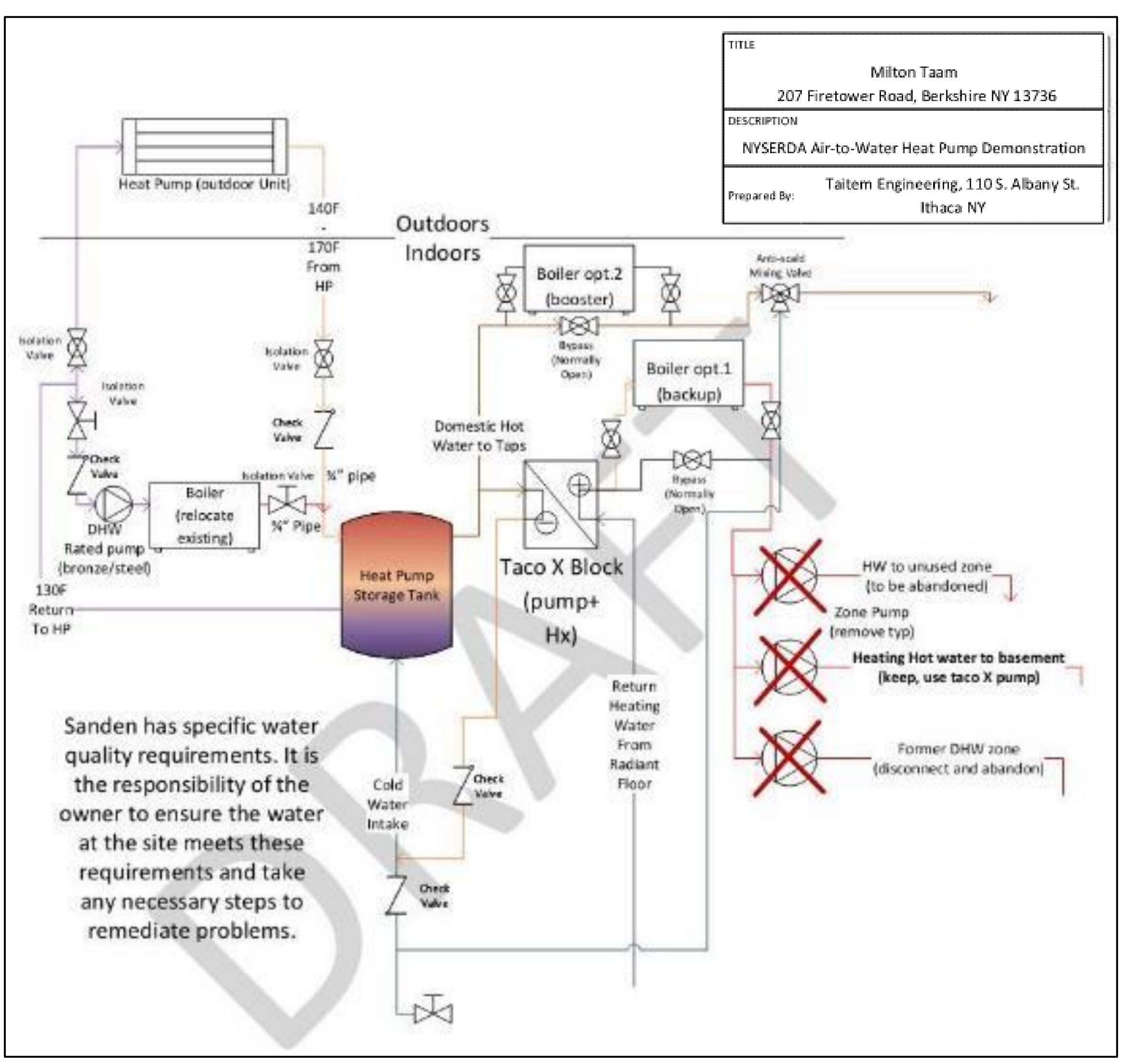
Probably something you can easily check on your next visit - just by measuring return temperature from the radiant floor - it should be in that 80-100F range.

Figure 29: Summary of Firetower Road revisions

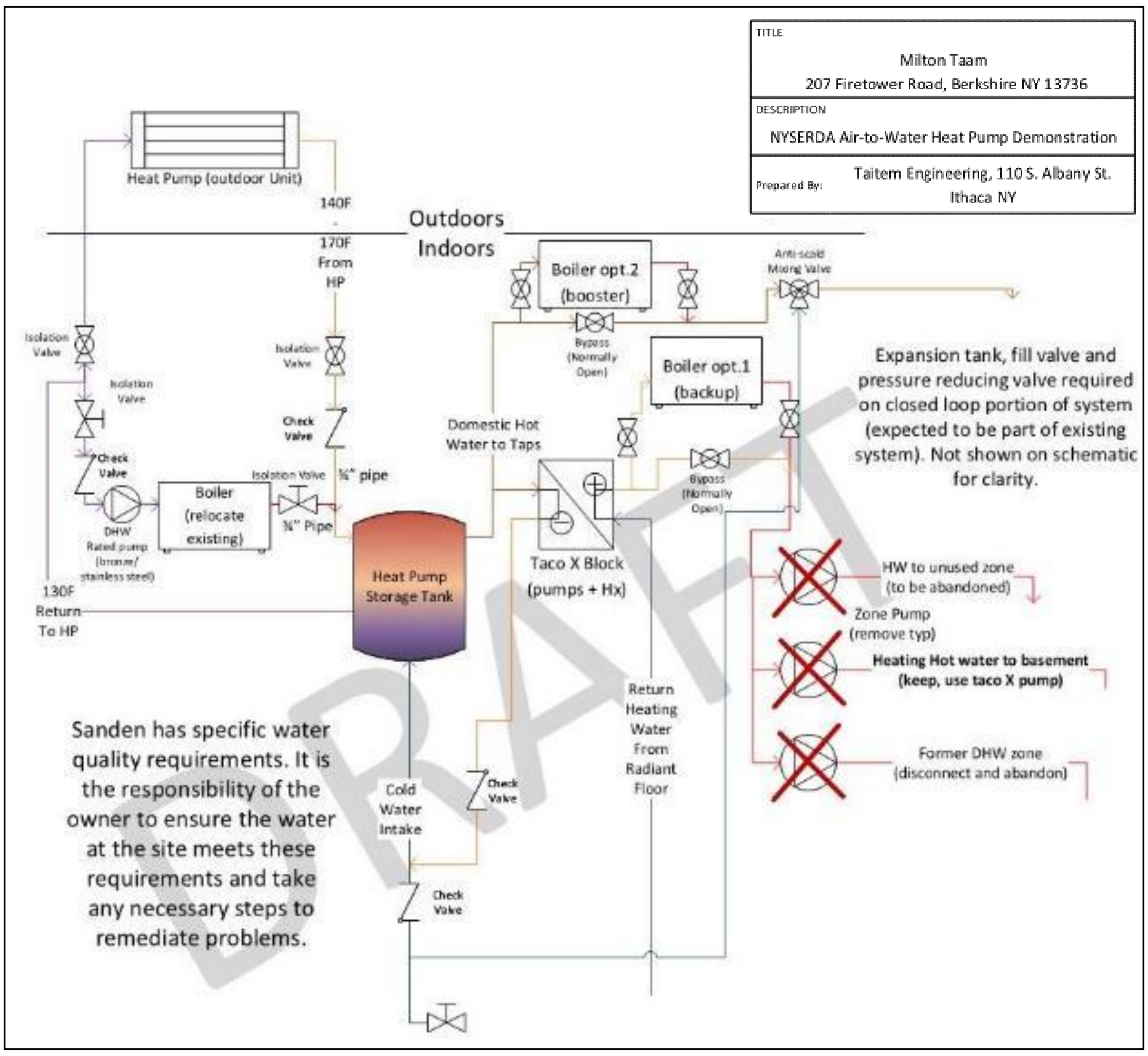
Rev 2: 2/20/18



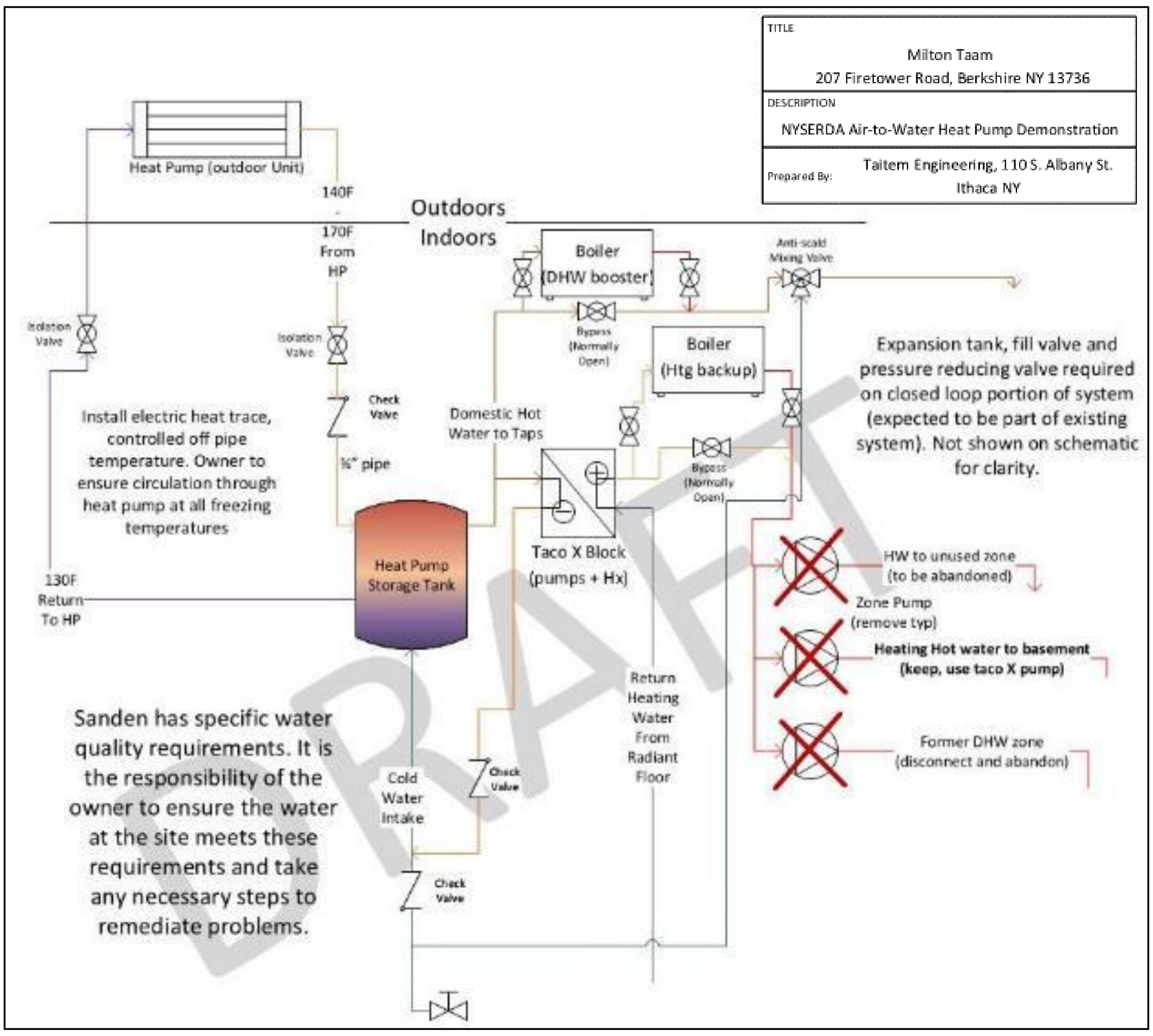
Rev 3: 2/21/18



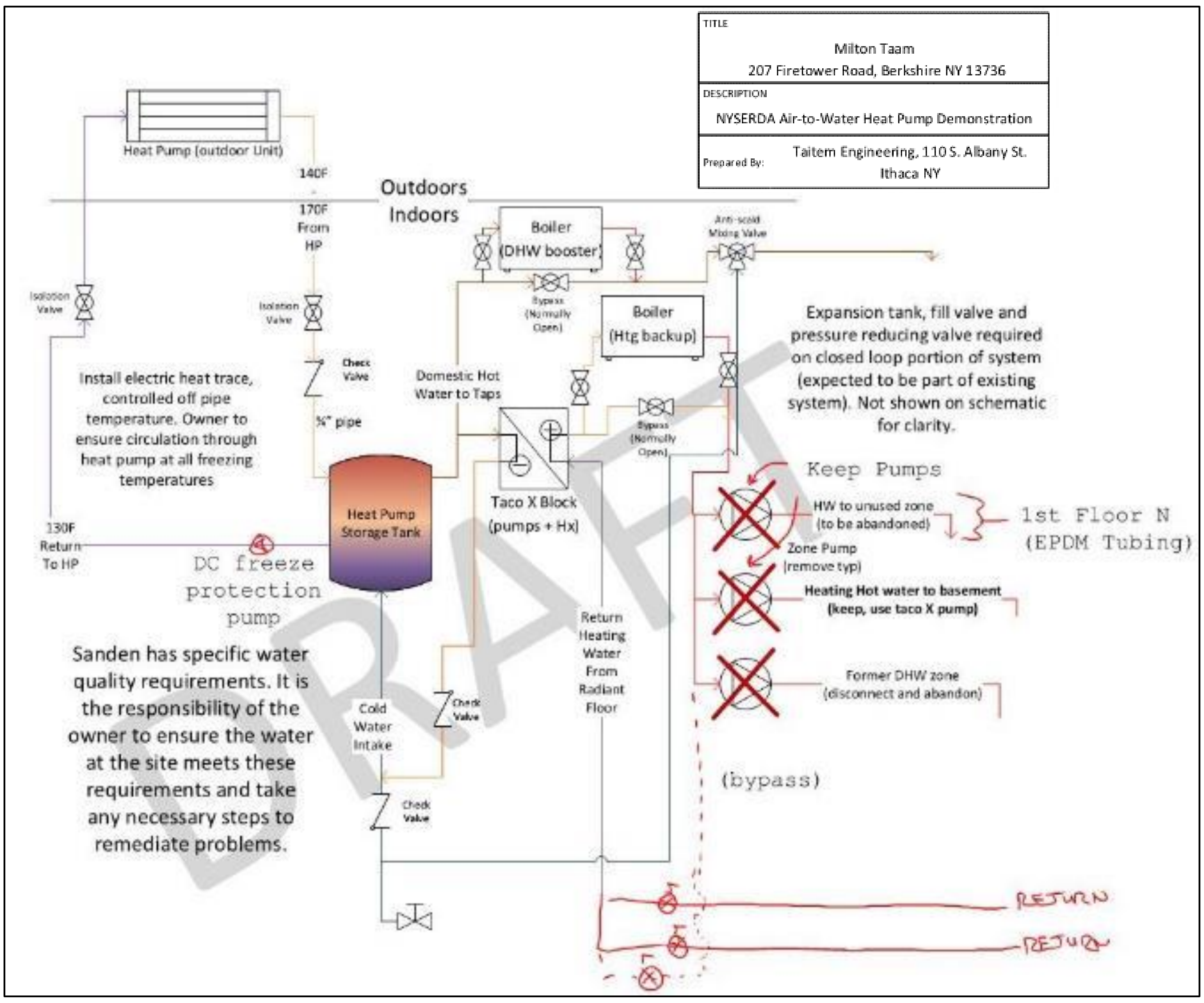
Rev 4: 2/21/18



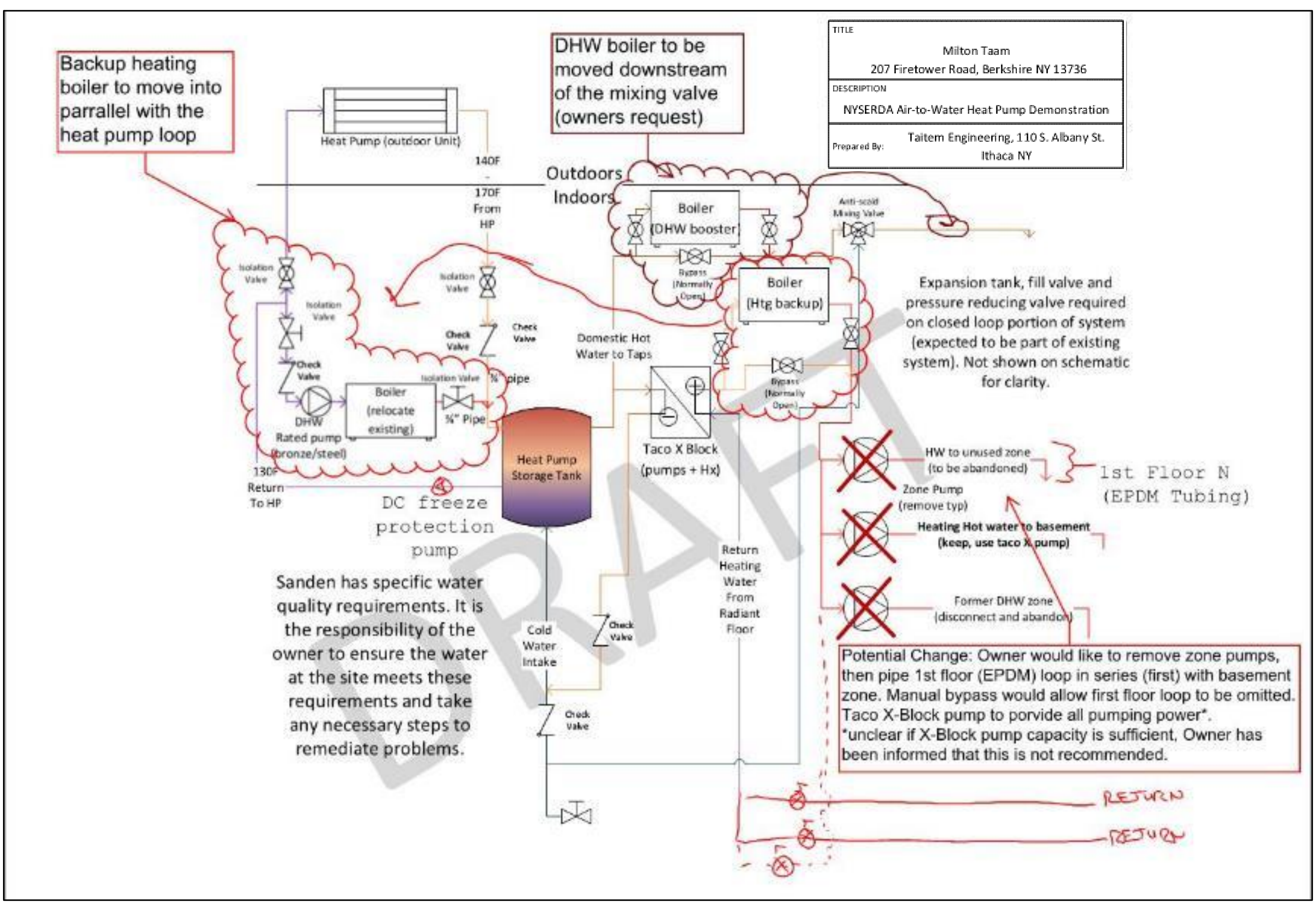
Rev 5: 6/12/18



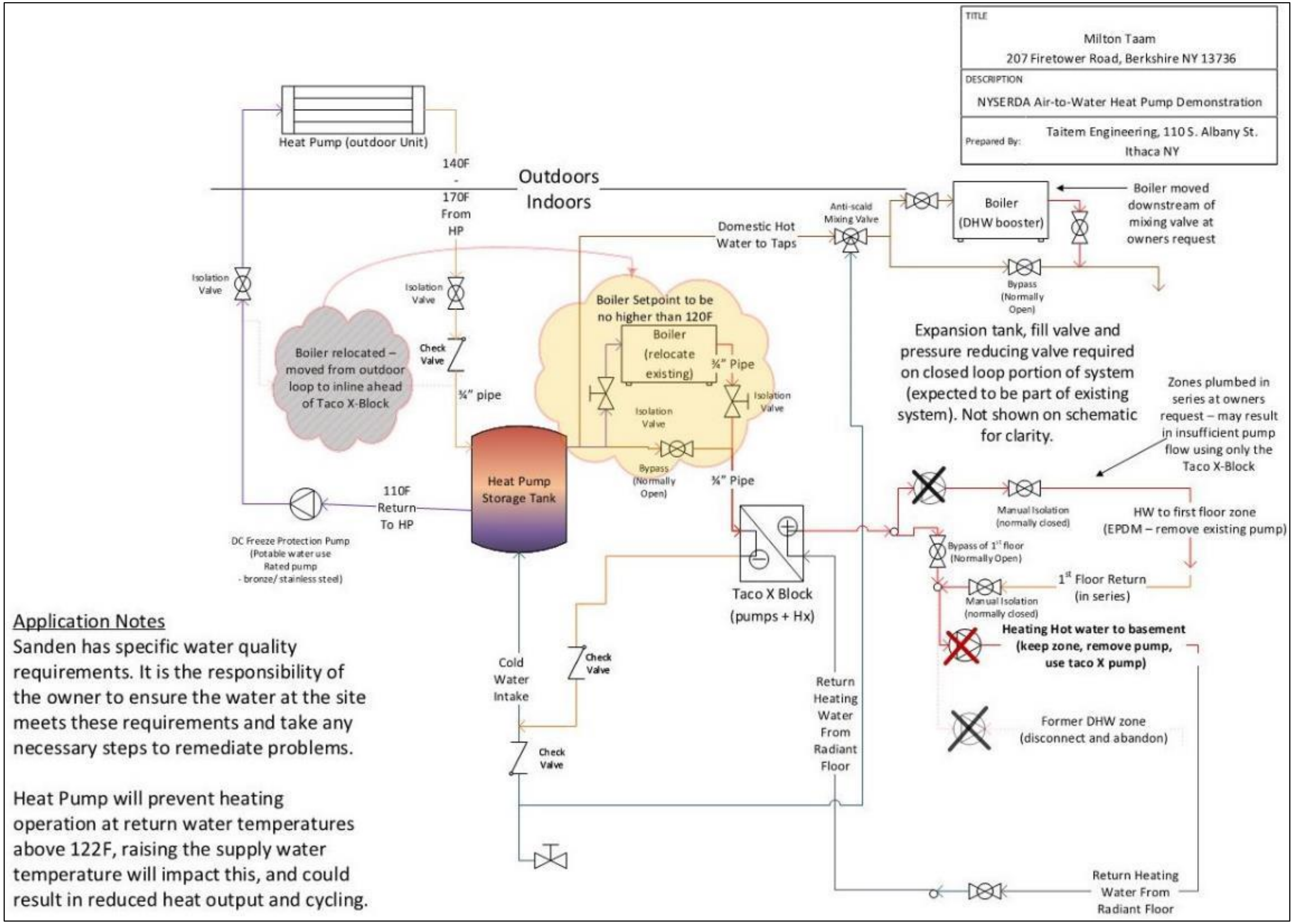
Rev 6: 6/19/18 (field markup of changes)



Rev 7: 10/18/18 (additional field revisions)



Rev 8: 11/21/18 (final consolidated release with field modifications)



A.3 Riders Mills Road: Supporting Calculations and Field Documents

Site Overview Photos

Figure 30: Riders Mills Road- Elevation Photo

View of the site from the driveway. Site consists of stand alone garage with no connection to house envelope, a two story central section, and a single story bedroom section at the rear. The main two story section has a finished basement that extends 2/3 the width of the upper floors, and continues under the single story bedroom section.

Figure 31: Riders Mills Road - Floor Plan

Rough floor plan of the site. Created from project field notes, 5/10/17

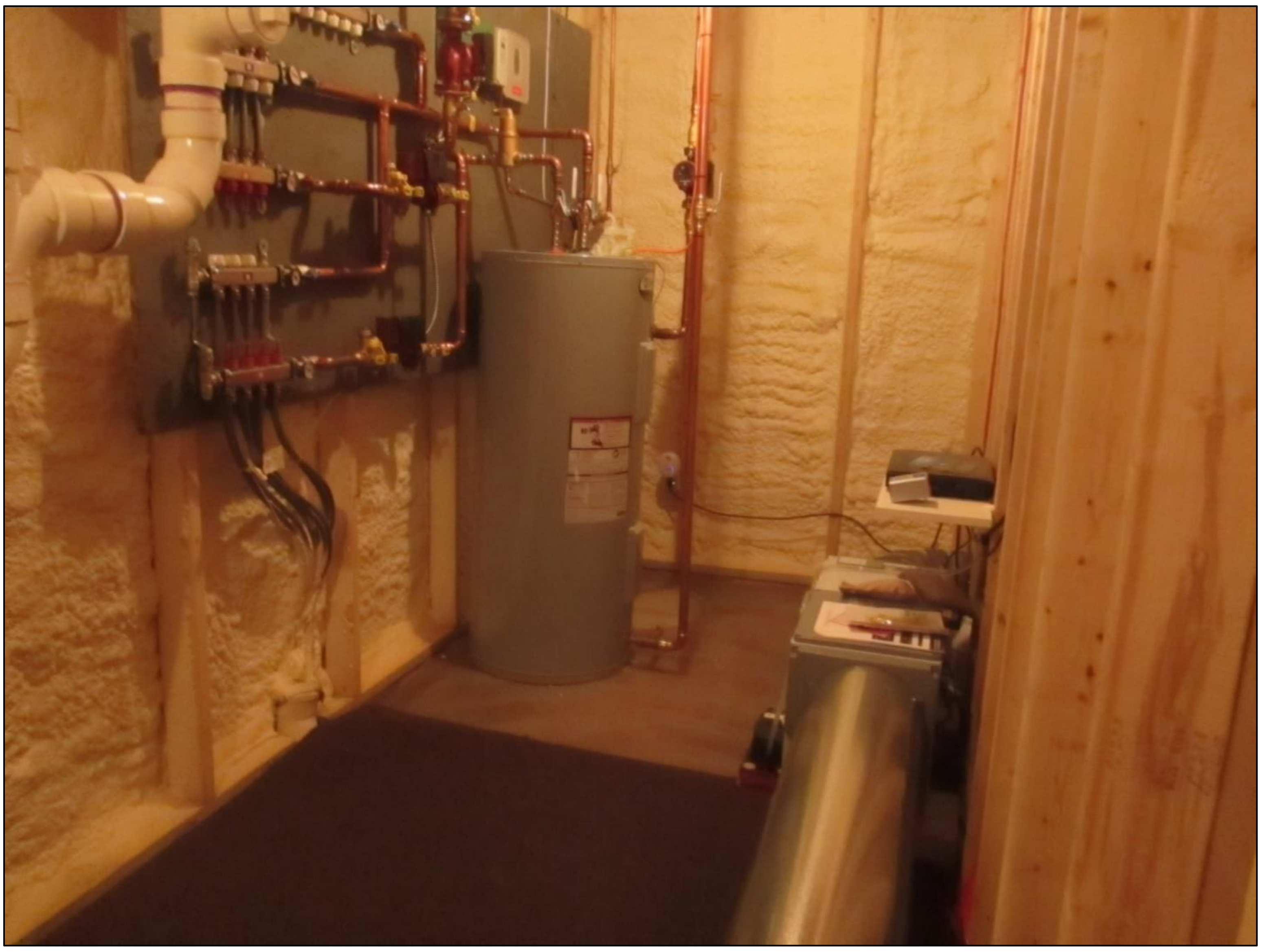
Installation Photos

Figure 32: Riders Mills Road - Outdoor Unit

Solstice Extreme Heat Pump unit installed outside at the Rider Mills Road site. 5/10/2018

Figure 33: Riders Mills Road - Buffer Tank and Pipe Layout

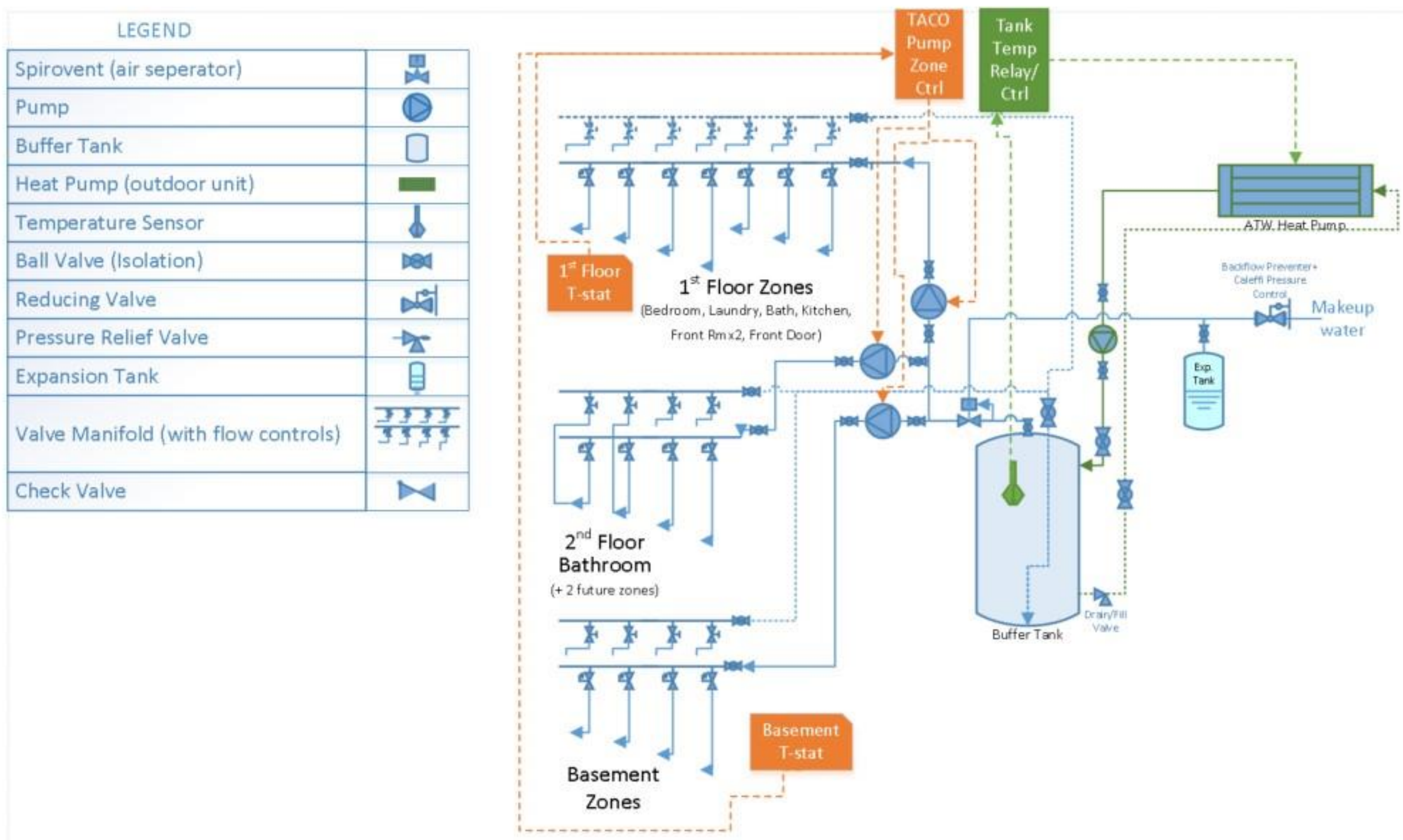
Buffer tank installed in mechanical room at the Rider Mills Road site. Note zoning controls for radiant floor system. 5/10/2018



Design Documents

Figure 34: Riders Mills Road - Pipe Schematic

As-built pipe layout as observed during our inspection on 5/10/2018



Not shown: Solar thermal assist, and domestic hot water preheating in progress as of 2/26/2019

Figure 35: Riders Mills Road – Buffer Tank Revisions Diagram

Owner provided schematic illustrating changes to system

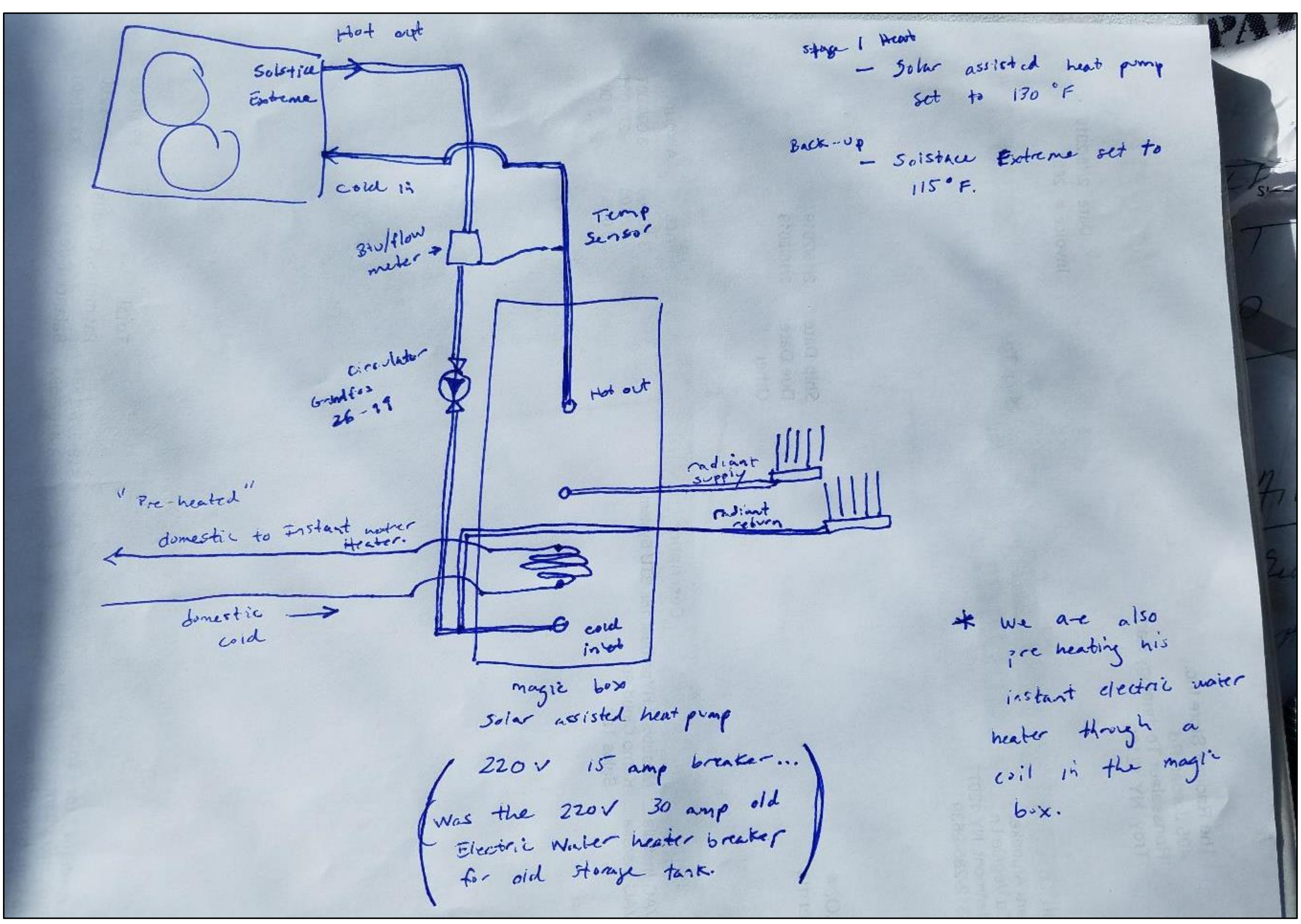
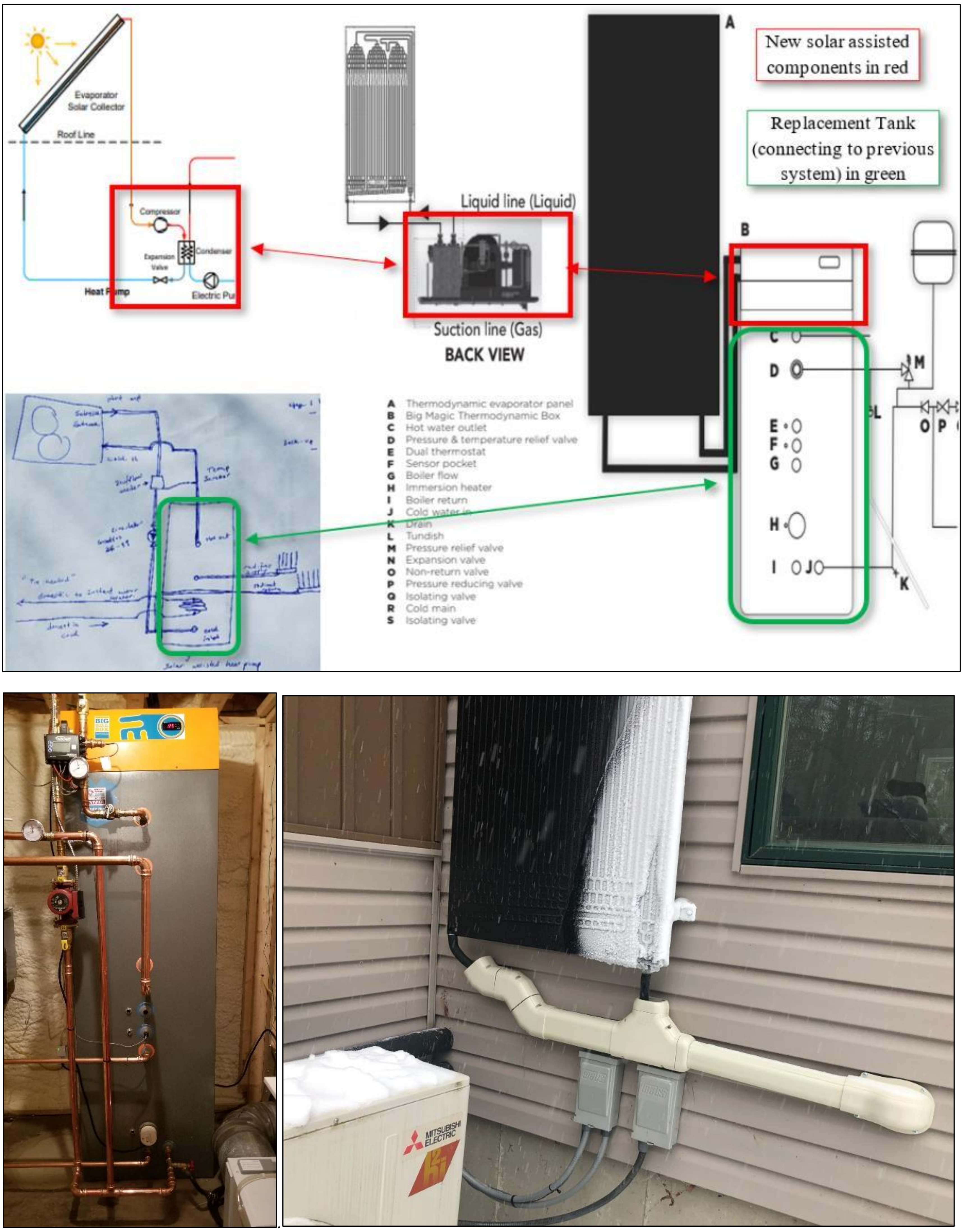


Figure 36: Riders Mills Road – Additions to Heating System

Revisions to systems and layout, as documented by the owner on 2/19/2019



A.4 Steuben Valley Road: Supporting Calculations and Field Documents

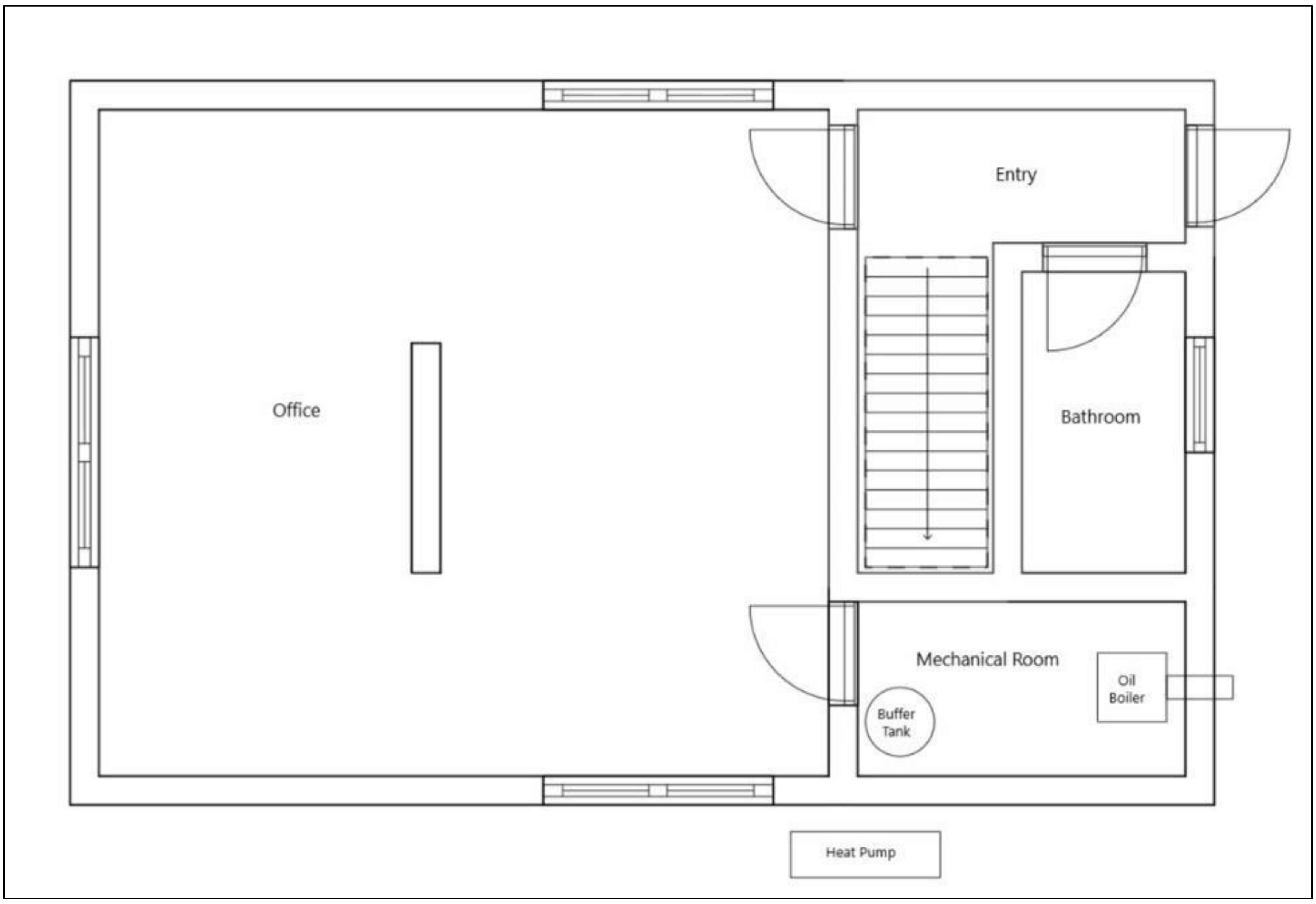
Site Overview Photos

Figure 37: Steuben Valley Road- Elevation Photo

View of the site from the driveway

Figure 38: Steuben Valley Road - Floor Plan

Rough floor plan of the first floor. From materials provided by Owner and site notes (5/30/2018)



Installation Photos

Figure 39: Steuben Valley Road - Outdoor Unit

Solstice Extreme Heat Pump unit installed outside at the Steuben Valley Road site. 5/30/2018

Figure 40: Steuben Valley Road - Buffer Tank

Buffer tank installed at Steuben Valley Road site. 5/30/2018

Design Documents

Figure 41: Steuben Valley Road – Site Location

Site location in context of larger property

Figure 42: Steuben Valley Road - Pipe Schematic

Piping Schematic for system, provided by owner during site visit (5/30/2018)

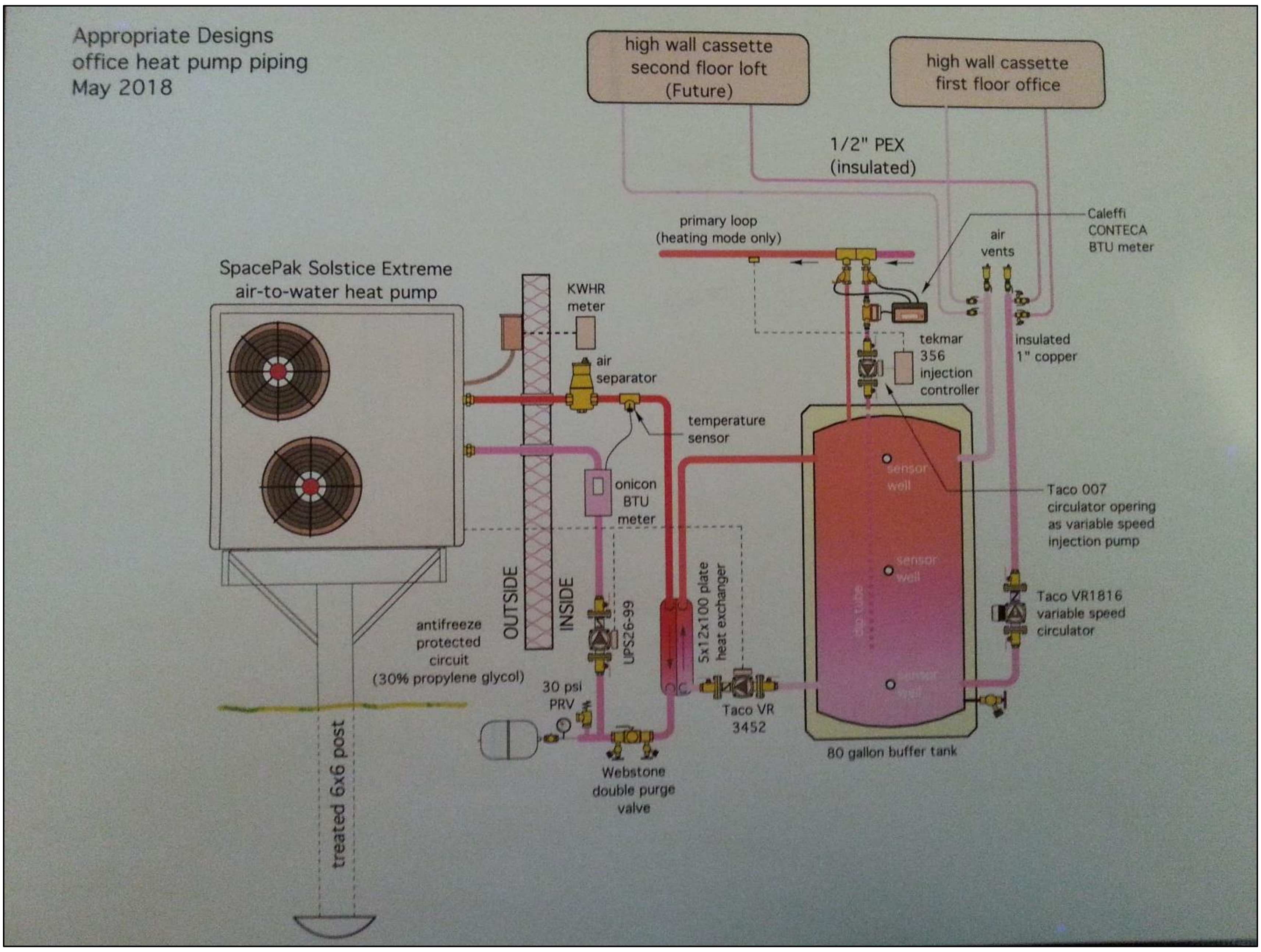


Figure 43: Steuben Valley Road – Thermal Envelope and Elevation Drawings

Details on radiant wall from owner

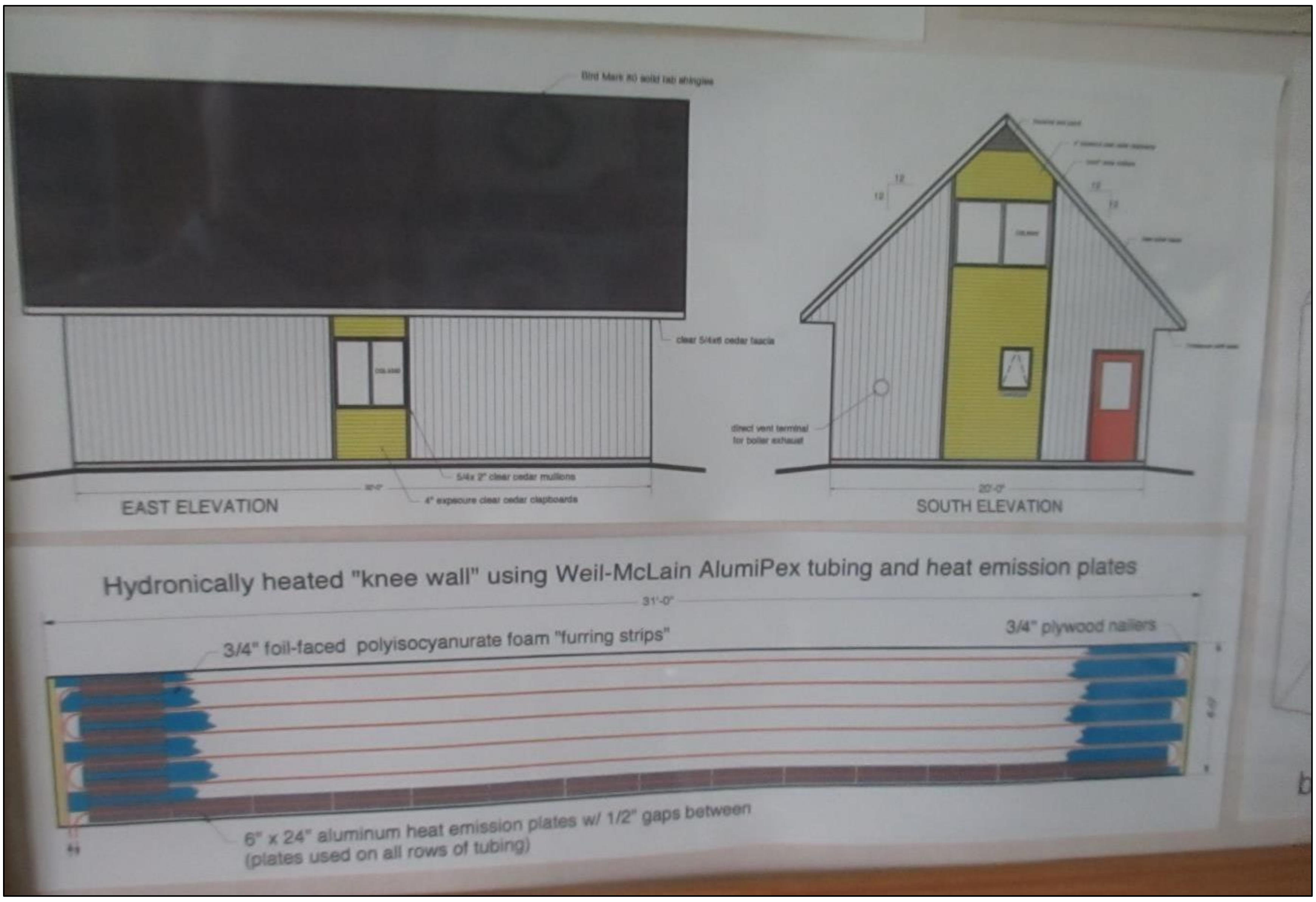


Figure 44: Steuben Valley Road – Radiant Floor Drawings

Details on radiant floor from owner

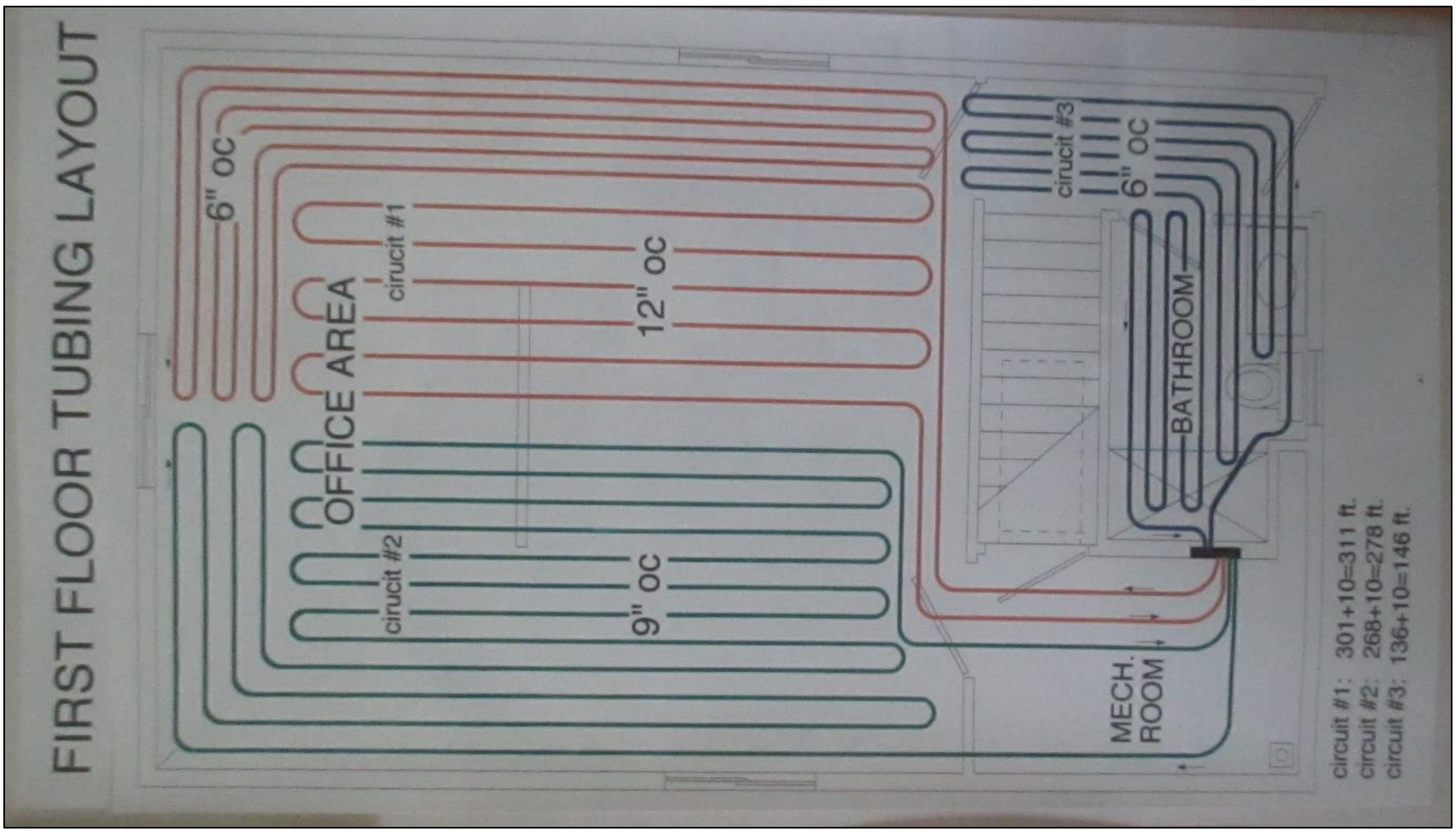


Figure 45: Steuben Valley Road – Radiant Wall and Previous System Schematic Drawing

Reference documents from owner

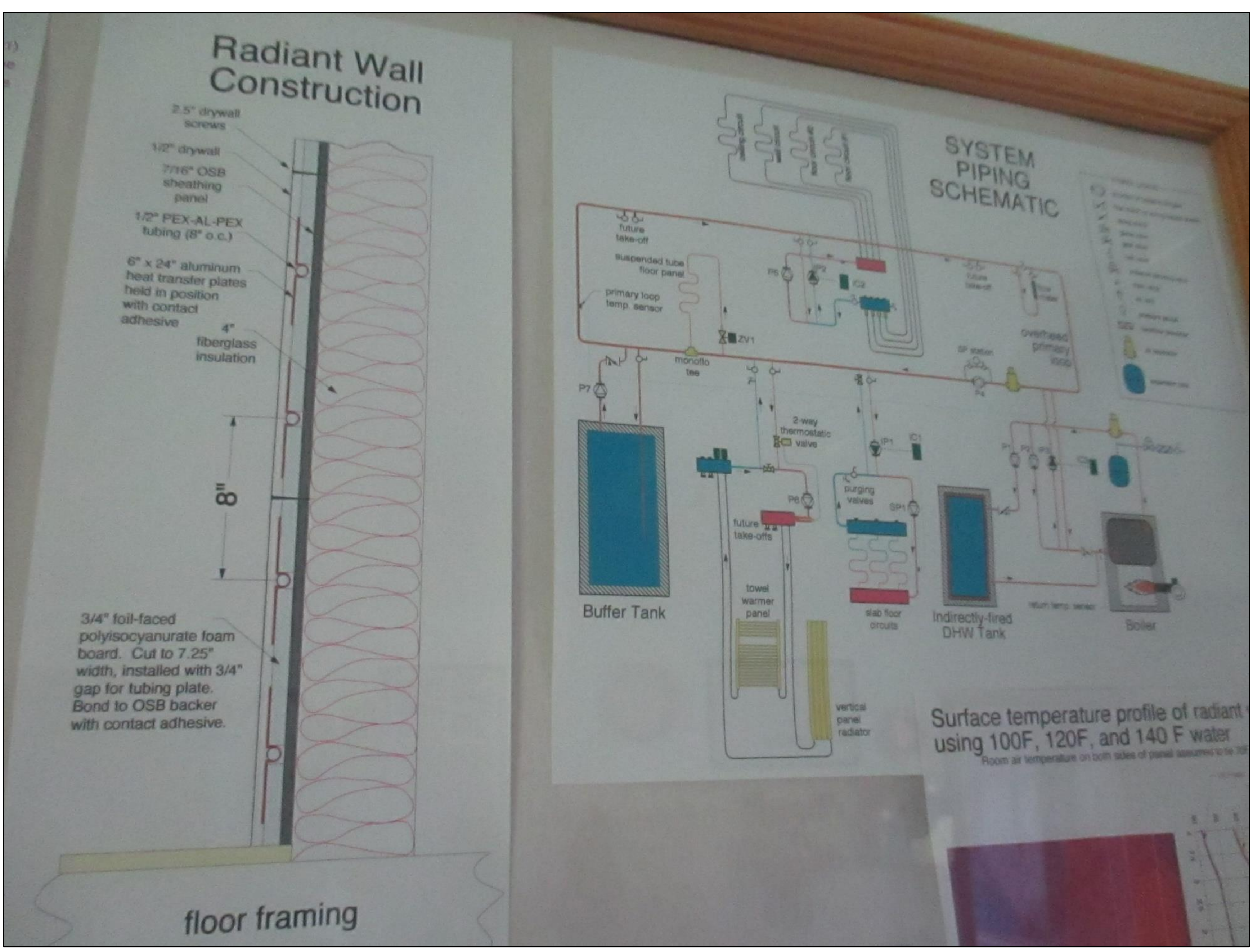
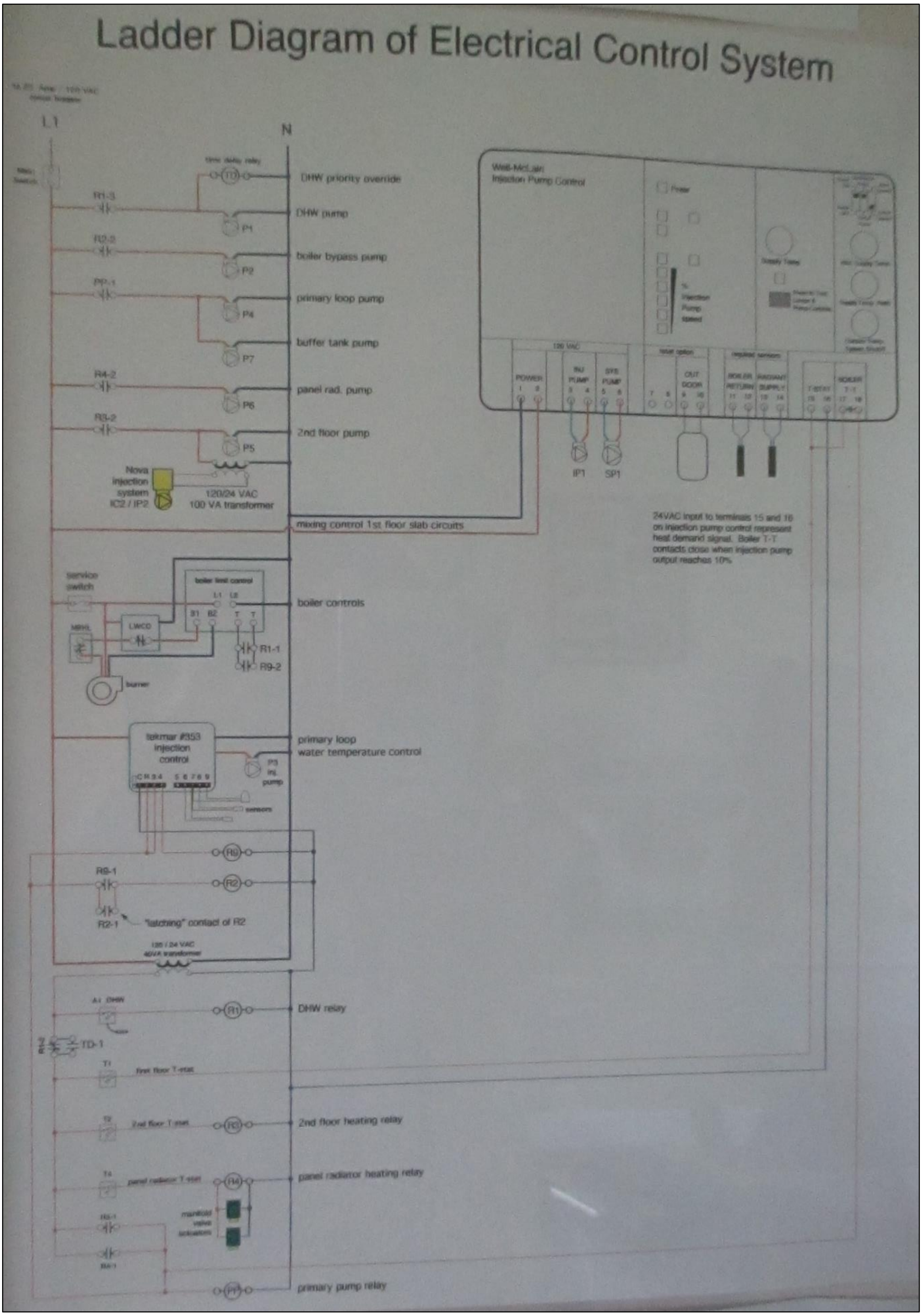


Figure 46: Steuben Valley Road – Controls logic Schematic Drawing

Reference documents from owner



A.5 Garrett Road: Supporting Calculations and Field Documents

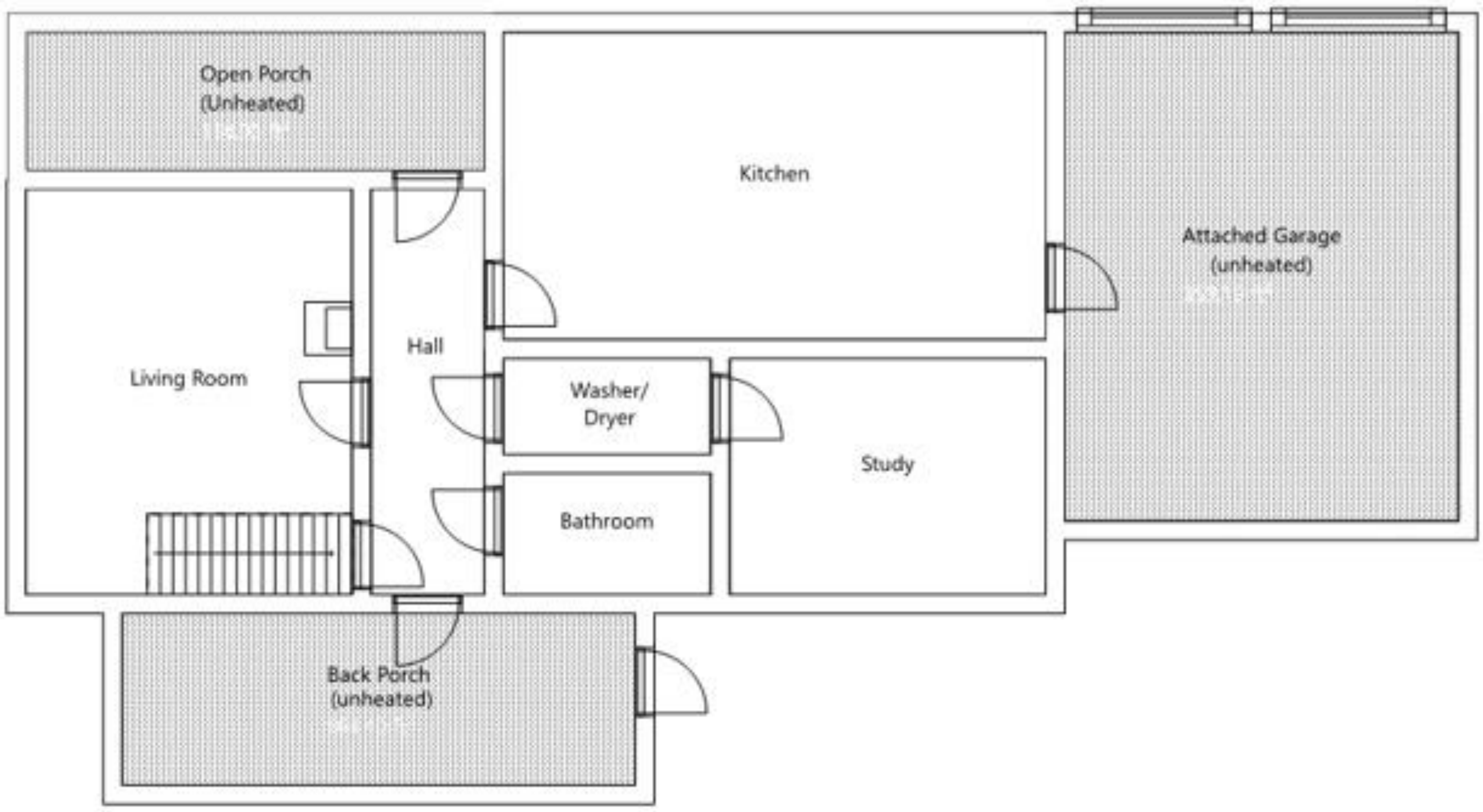
Site Overview Photos

Figure 47: Garrett Road- Elevation Photo

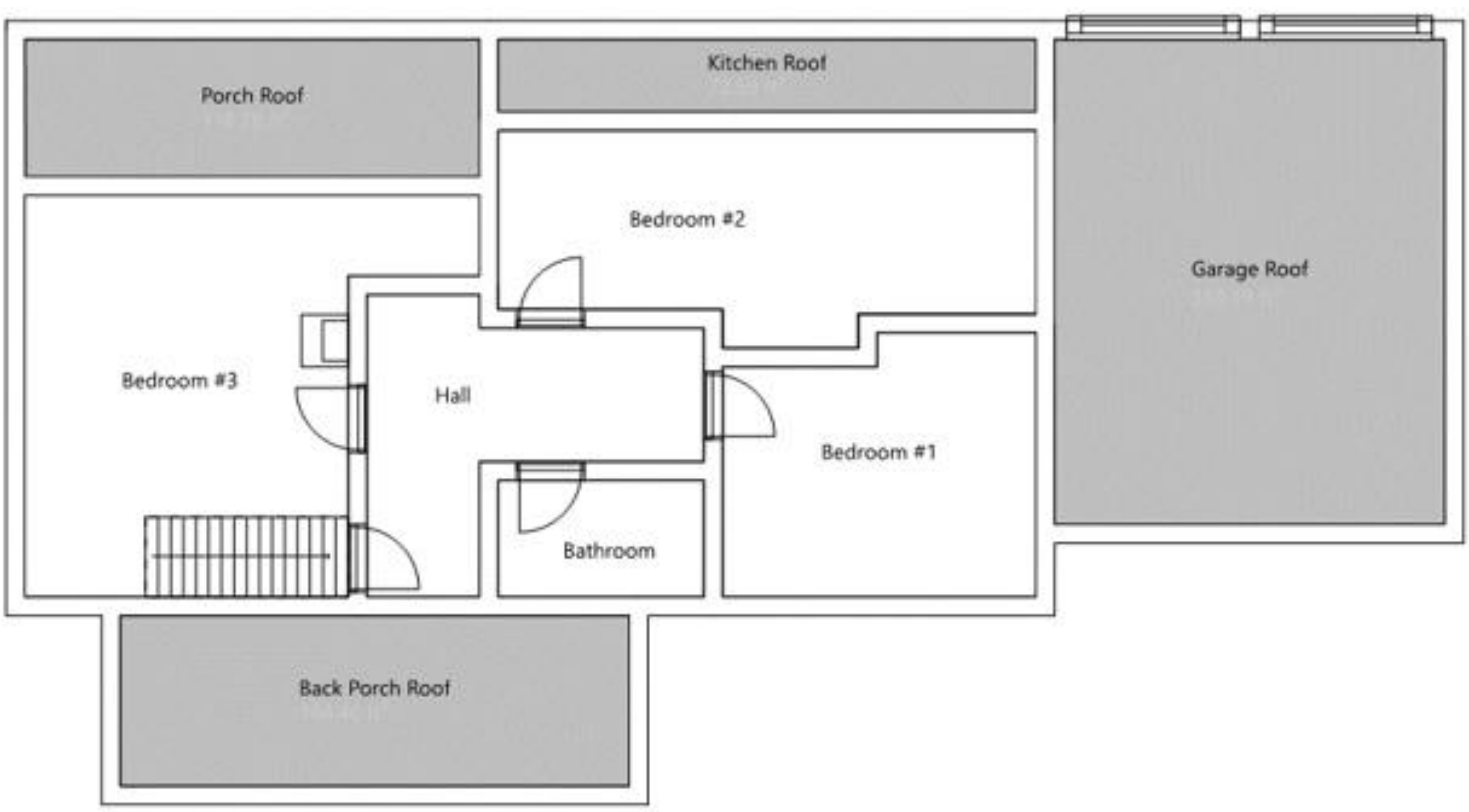
View of the site from the driveway. Attached garage is single story.

Figure 48: Garrett Road – First and Second Floor Plans

First Floor Plan, followed by Second Floor Plan



First Floor



Second Floor

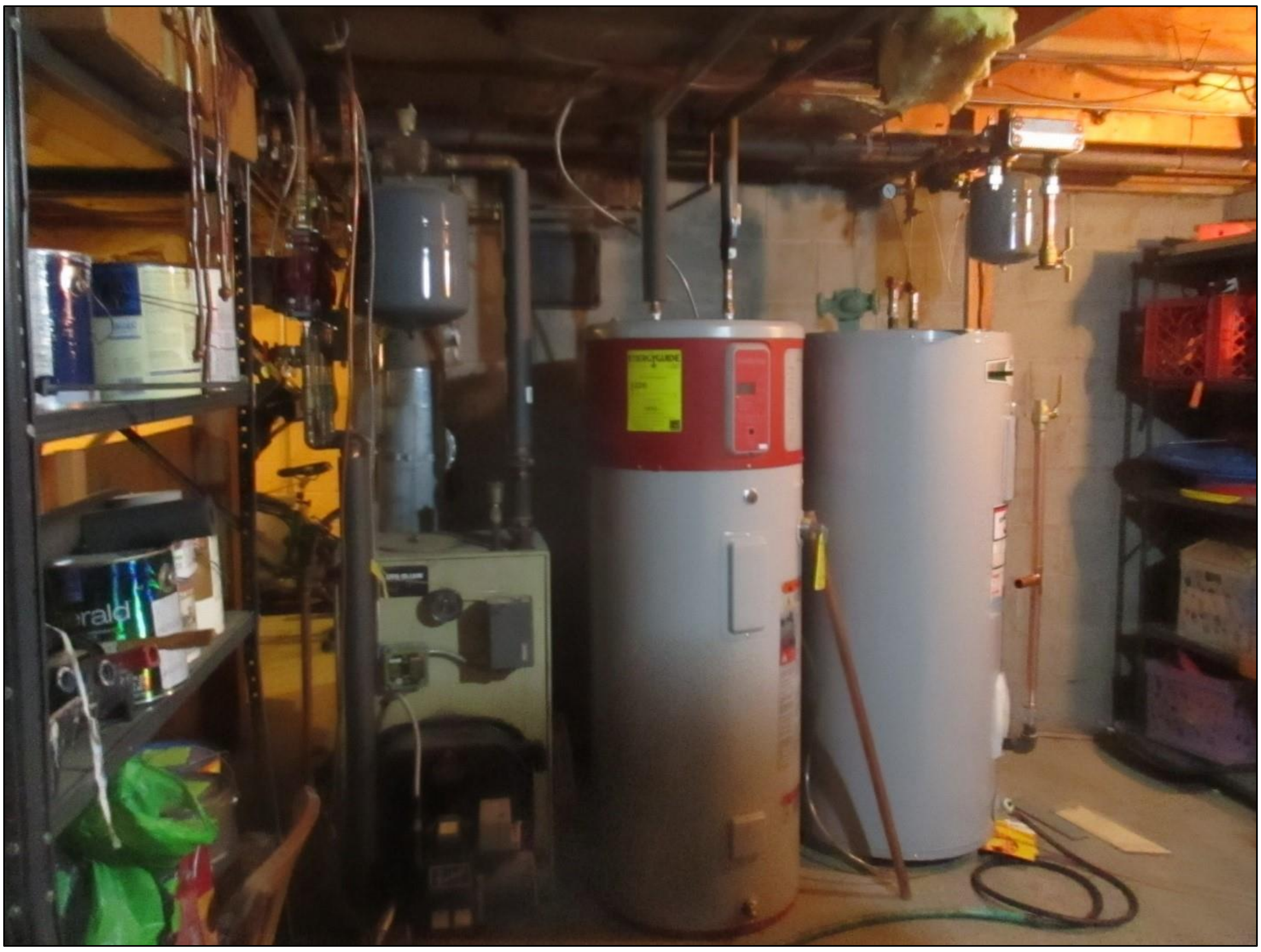
Installation Photos

Figure 49: Garrett Road - Outdoor Unit (12/17/18)

Outdoor unit at Garrett Road

Figure 50: Garrett Road - Buffer Tank

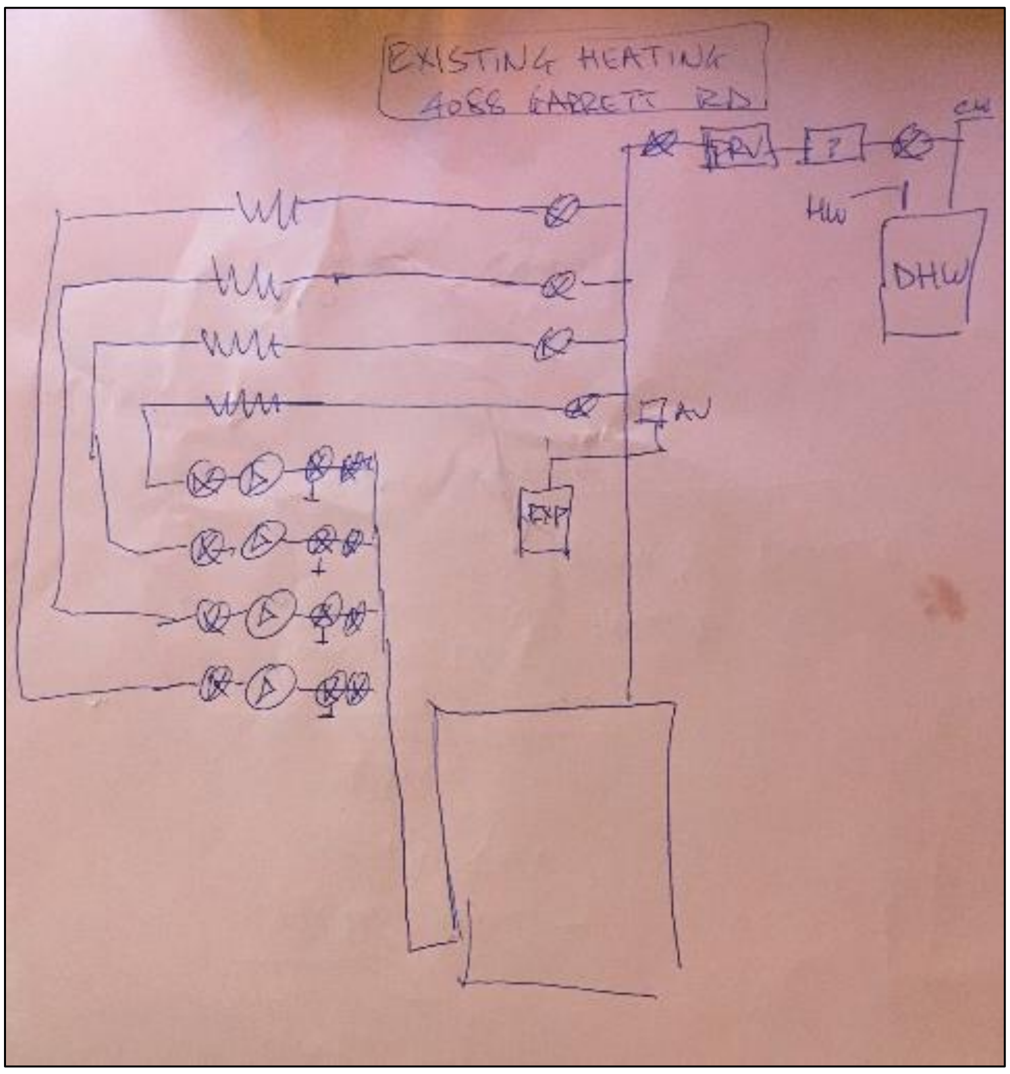
New buffer tank, adjacent to existing oil boiler, and domestic hot water system.



Design Documents

Figure 51: Garrett Road – Existing System Diagrams

Existing Field verification of system layout- provided by owner



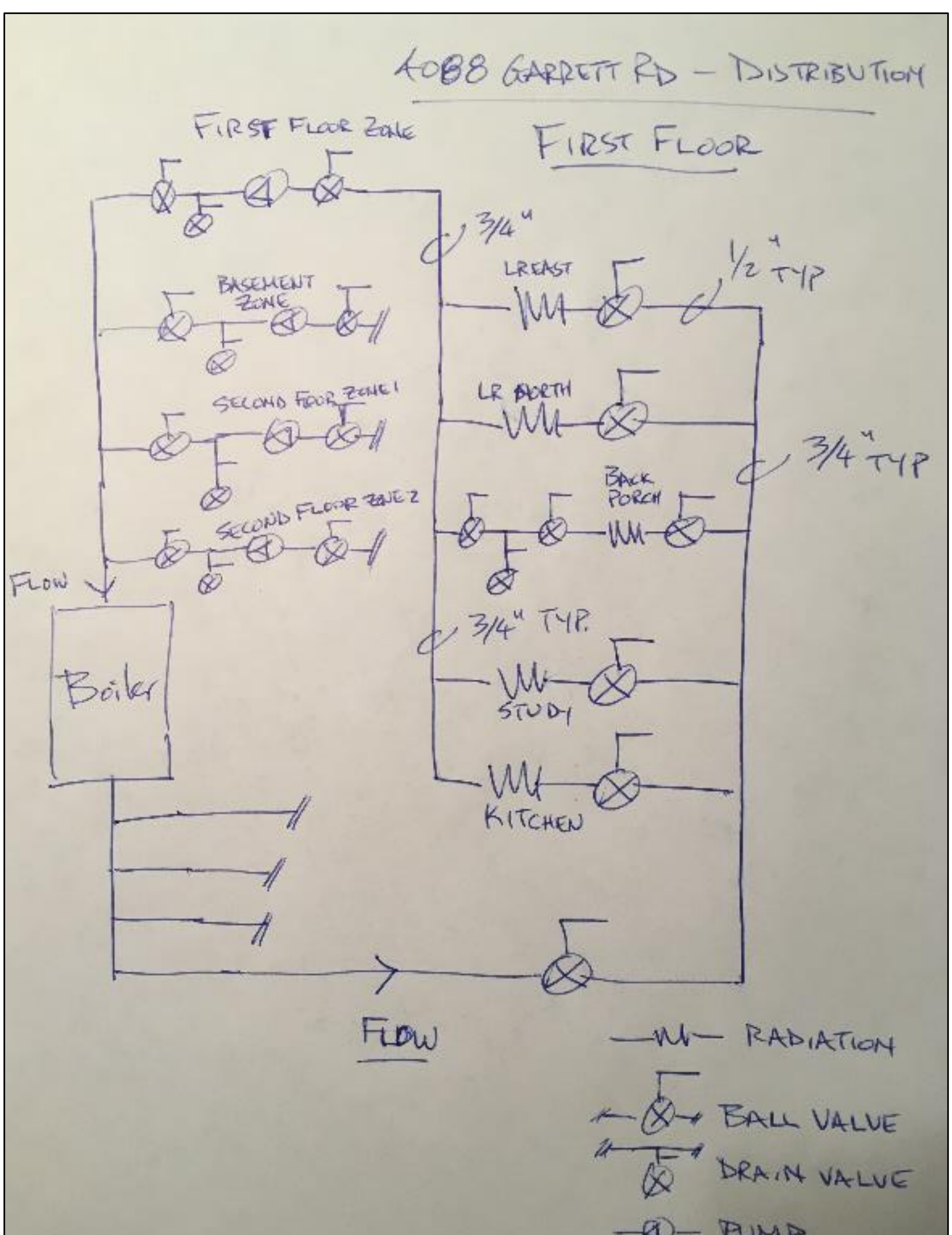


Figure 52: Garrett Road – Updated Existing System Diagrams

Existing Field verification of system layout, provided by owner, including a later release showing new work performed to increase distribution output capacity

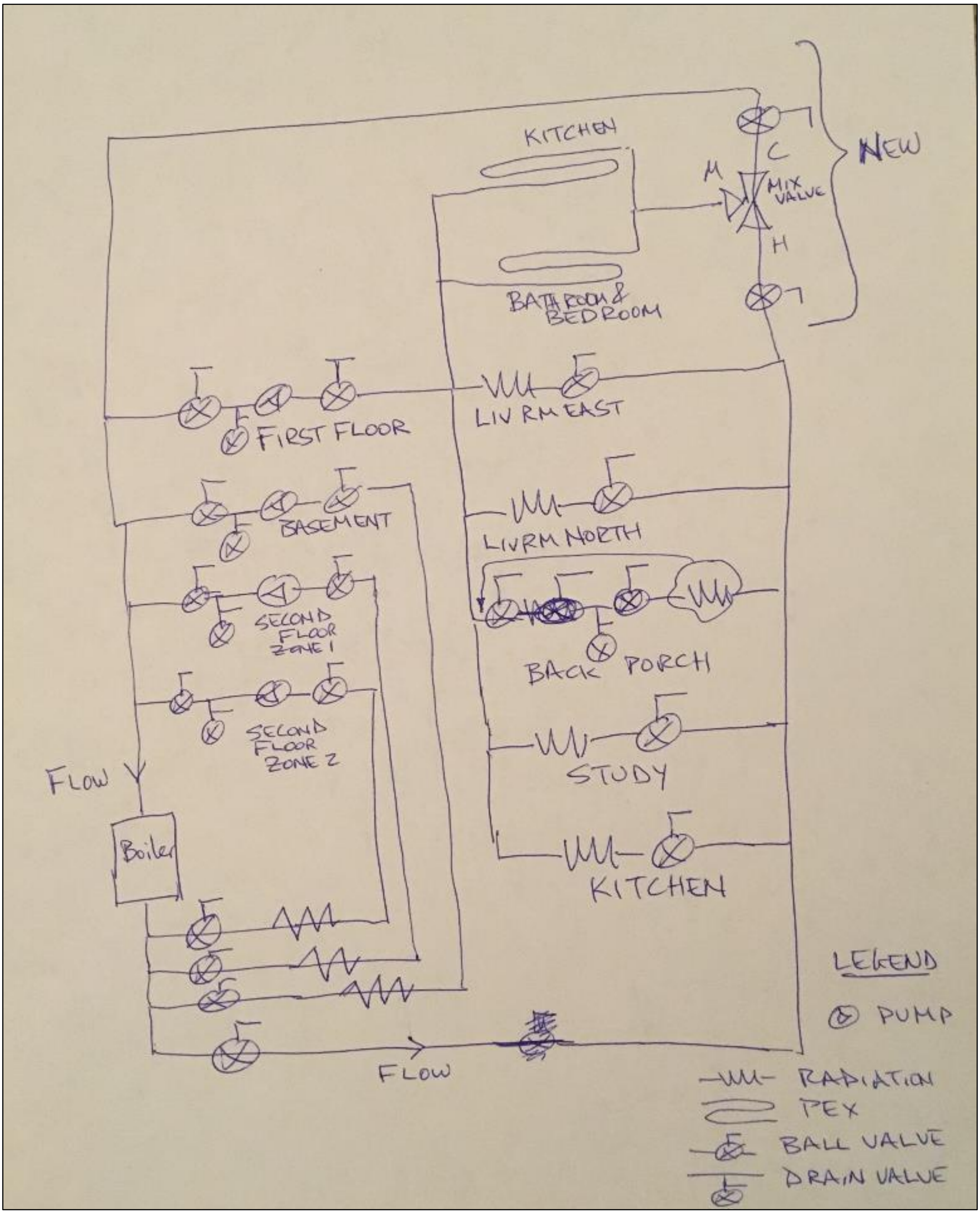


Figure 53: Garrett Road – Existing System Diagrams

Schematic layout of provided existing system details

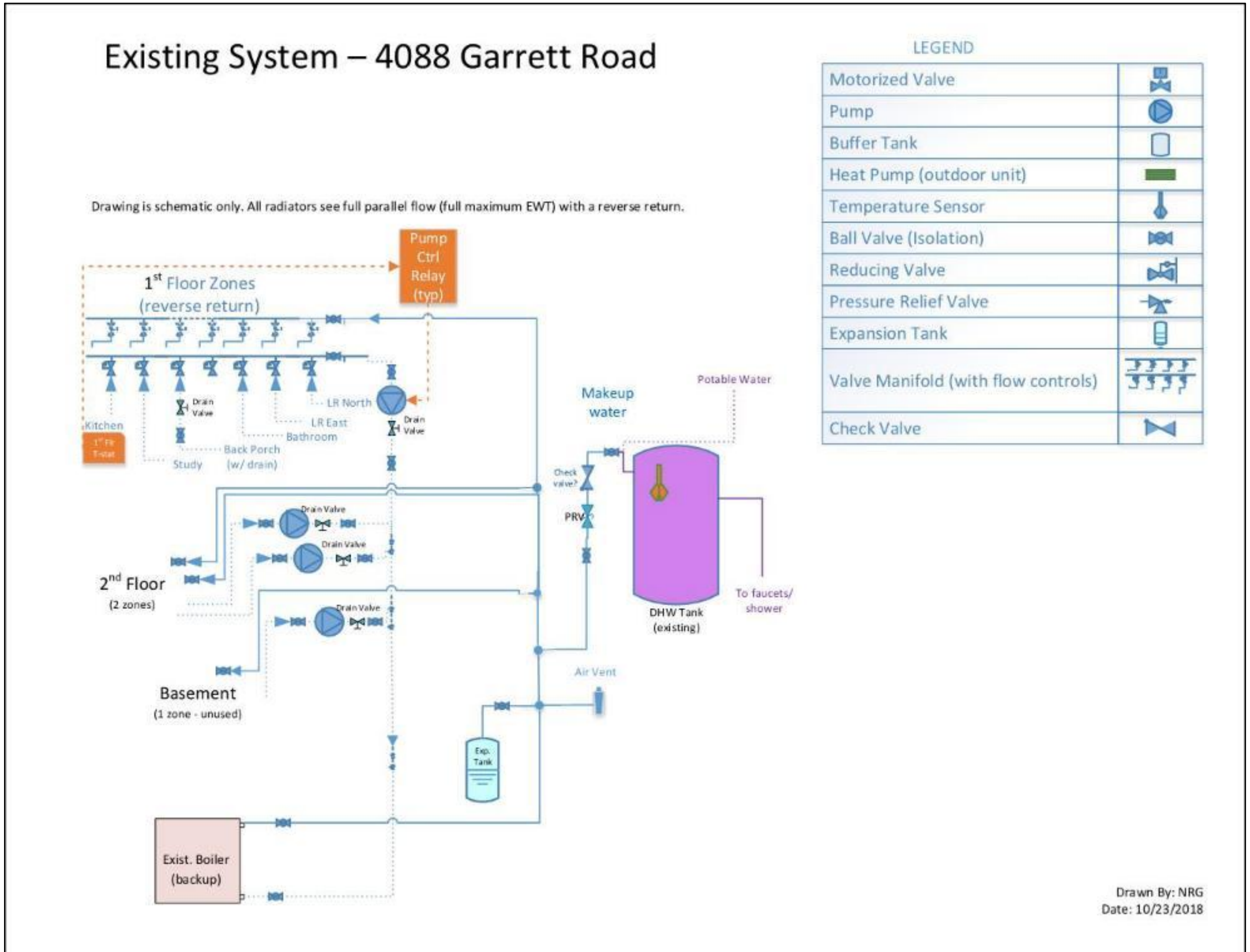


Figure 54: Garrett Road - Pipe Schematic

System layout for Garrett Road Site – Note, heat exchanger removed and direct supply connection changed to a buffer tank side connection (not shown) 2/23/2019

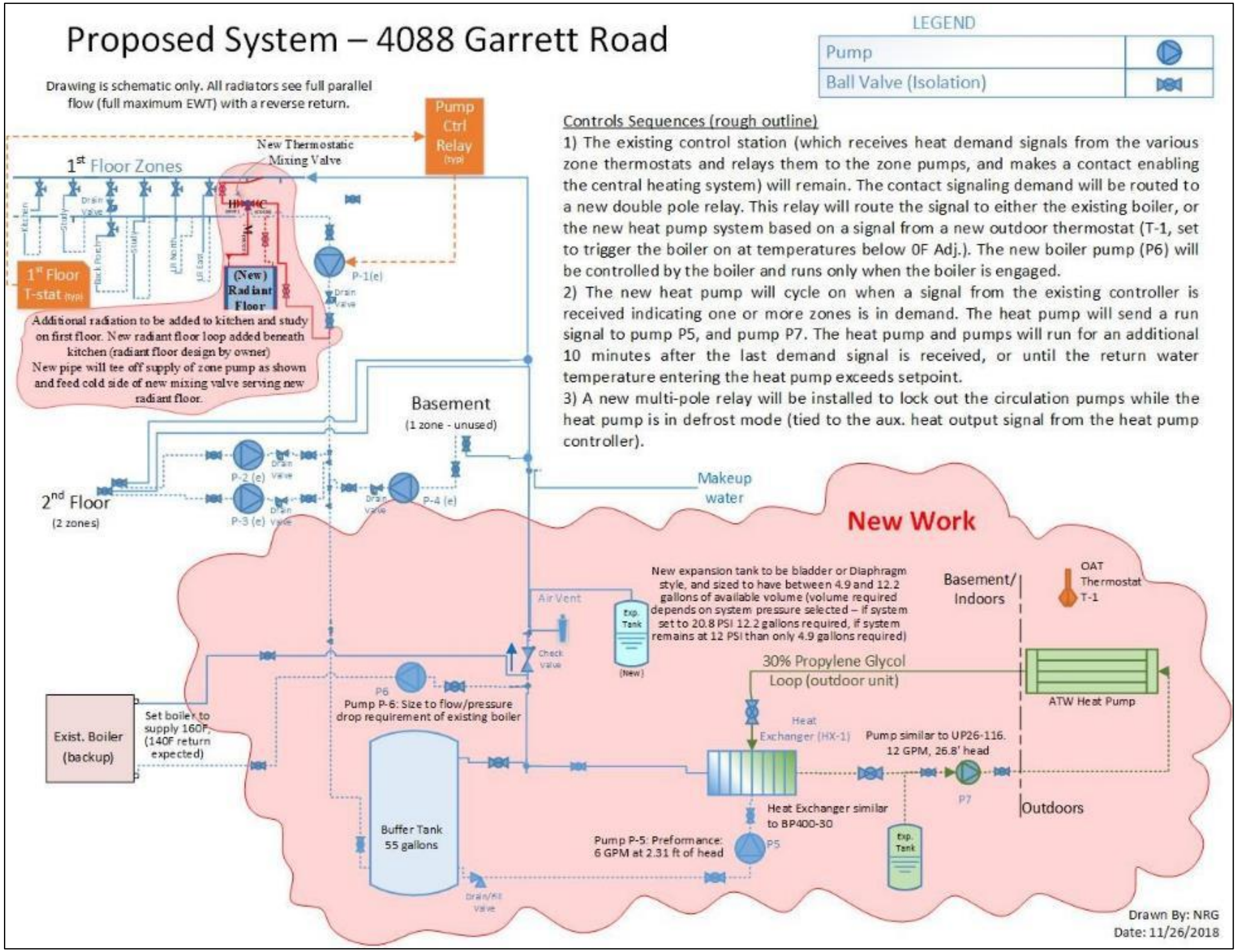


Figure 55: Garrett Road - Distribution Capacity and Temperature Calculations- 1 of 2

Spreadsheet calculation, with reference tables, used to calculate existing distribution system capacity at various average water temperatures, and flow rates (Kitchen and Study)

Equations:		Assumptions			Radiation:		
Q=UAdT	(conductive)	Basement	50	Deg. F	Kitchen	9	feet residential hydronic baseboard. NOTE: KITCHEN IS COLD IN WINTER, EVEN THOUGH IT HAS THE THERMOSTAT. 9' IS NOT ENOUGH TO MEET LOAD.
Q=1.08*CFM*dT	(infiltration)	Garage	30	Deg. F	Study	7	feet residential hydronic baseboard. Note: This rooms is warm enough in winter. We have to cut back on water flow to this room, otherwise it's too hot.
U=1/R		Outside	0	Deg. F			
		Inside	70	Deg. F			

Conductive Heat Loss Calculations

Room	Surface	Width (ft)	Height (ft) or Length	Area [SF]	Faces	Adjacent	Temp. [F]	R-value	U-Value	Heat Loss [Btu/hr]	Notes
Kitchen	Wall	15	8	120	East	Outdoors	0	19	0.053	442.1	
Kitchen	Wall	15.5	8	124	South	Garage	30	13	0.077	381.5	R-value assumed - looks like 2x4 frame, not 2x6 like the exterior walls.
Kitchen	Door	2.5	7.5	18.8	South	Garage	30	1	1	750.0	Guess on R-value. Interior door!
Kitchen	Ceiling	15	5	75	NA	Outdoors	0	19	0.053	276.3	R-value assumed - can't check, concealed. This portion of the kitchen ceiling is exposed to a small vented attic.
Kitchen	Ceiling	15	10.5	158	NA	Upstairs	70	100	0.01	0.0	Upstairs is heated
Kitchen	Floor	15.5	15	233	NA	Basement	50	19	0.053	244.7	R-value estimated - looks like 6" fiberglass between basement joists. Basement is usually at 60 F in winter. Will be less without boiler down there, I expect it to be more like 50 F.
Kitchen	Window	3.833	4.8333333	18.5	East	Outdoors	0	2	0.5	648.5	Double pane window, assume not low-e or gas-filled, 1984 vintage
Kitchen	Window	2.875	2.8333333	8.15	East	Outdoors	0	2	0.5	285.1	Double pane window, assume not low-e or gas-filled, 1984 vintage
Volume [CF]	1860		Air Leakage	0.7	[ACH]				Total Conductive:	3028.3	Grand Total
OAT [F]	0			21.7	[CFM]				Total Infiltration	1640.5	4668.8 [Btu/hr]
Study	Wall	9.75	8	78	West	Outdoors	0	19	0.053	287.4	
Study	Wall	5	8	40	South	Outdoors	0	19	0.053	147.4	
Study	Wall	11	8	88	South	Garage	30	13	0.077	270.8	R-value assumed - looks like 2x4 frame, not 2x6 like the exterior walls.
Study	Floor	5.5	9.75	53.6	NA	Basement	50	5	0.2	214.5	R-value estimated - looks like 6" fiberglass between basement joists. Basement is usually at 60 F in winter. Will be less without boiler down there, I expect it to be more like 50 F.
Study	Floor	5.5	9.75	53.6	NA	Basement	50	19	0.053	56.4	R-value estimated - looks like 6" fiberglass between basement joists. Basement is usually at 60 F in winter. Will be less without boiler down there, I expect it to be more like 50 F.
Study	Ceiling	11	9.75	107	NA	Upstairs	70	100	0.01	0.0	Upstairs is heated
Study	Window	3.083	2.6666667	8.22	West	Outdoors	0	2	0.5	287.8	Double pane window, assume not low-e or gas-filled, 1984 vintage
Study	Window	3.083	2.6666667	8.22	South	Outdoors	0	2	0.5	287.8	Double pane window, assume not low-e or gas-filled, 1984 vintage
Volume [CF]	858		Air Leakage	0.5	[ACH]				Total Conductive:	1552.0	Grand Total
OAT [F]	0			7.15	[CFM]				Total Infiltration	540.5	2092.5 [Btu/hr]

Figure 56: Garrett Road - Distribution Capacity and Temperature Calculations- 2 of 2

Spreadsheet calculation, with reference tables, used to calculate existing distribution system capacity at various average water temperatures, and flow rates (Kitchen and Study)

Source: http://www.ahrinet.org/App_Content/ahri/files/Certification/ComFinnedTube_AHRICertDirectory.pdf

Heat Loss

Kitchen:	4668.8	Btu/hr
Study:	2092.5	Btu/hr

Existing Radiation

Kitchen:	9	Ft baseboard
Study:	7	Ft baseboard

The baseboard is very typical residential, 3/4" copper pipe aluminum fin, single row, looks like about 6 fins per inch, b

Assumptions

Existing Hot Water Temperature			Average Water Temperature		
Supply Water Temp	180	F	170	F	
Return Water Temp	160	F	0.61	AHRI Factor	

Indoor Temperature: 70 F

Proposed Hot Water Temperature			Average Water Temperature		
Supply Water Temp	120	F	110	F	
Return Water Temp	100	F	0.20	AHRI Factor	

Existing (Standard) Radiator Output

Basis of Design:	Sterling R02, 3/4", 60 fin/ft 950 Btu/ft/hr A
AHRI (at STP)	950 Btuh/LF
Notes	Kitchen is cold, study warm - use to true up performance

Proposed Radiator (see table below for start)

Make	
Model	
AHRI rating	950 [btu/hr/ft]

AWT [F]	Factor
100	0.15
110	0.20
120	0.26
130	0.33
140	0.40
150	0.45
155	0.49
160	0.53
165	0.57
170	0.61
175	0.65
180	0.69
185	0.73
190	0.78
195	0.82
200	0.86
205	0.91
210	0.95
215	1.00
220	1.05
225	1.09
230	1.15
235	1.20
240	1.25

TABLE C

Factors use to convert AHRI Steam Ratings to Hot Water Ratings at Temperature Indicated

Average Radiator Temperature	Factor
100	0.15
110	0.20
120	0.26
130	0.33
140	0.40
150	0.45
155	0.49
160	0.53
165	0.57
170	0.61
175	0.65
180	0.69
185	0.73
190	0.78
195	0.82
200	0.86
205	0.91
210	0.95
215	1.00
220	1.05
225	1.09
230	1.14
235	1.20
240	1.25

TABLE D

Factors for Determining Outputs at Water Flow Rates of less than 3 ft/sec

Flow Rate	Factor
3.00	1.000
2.75	0.996
2.50	0.992
2.25	0.988
2.00	0.984
1.75	0.979
1.50	0.973
1.25	0.966
1.00	0.957
0.75	0.946
0.50	0.931
0.25	0.905

Calculations

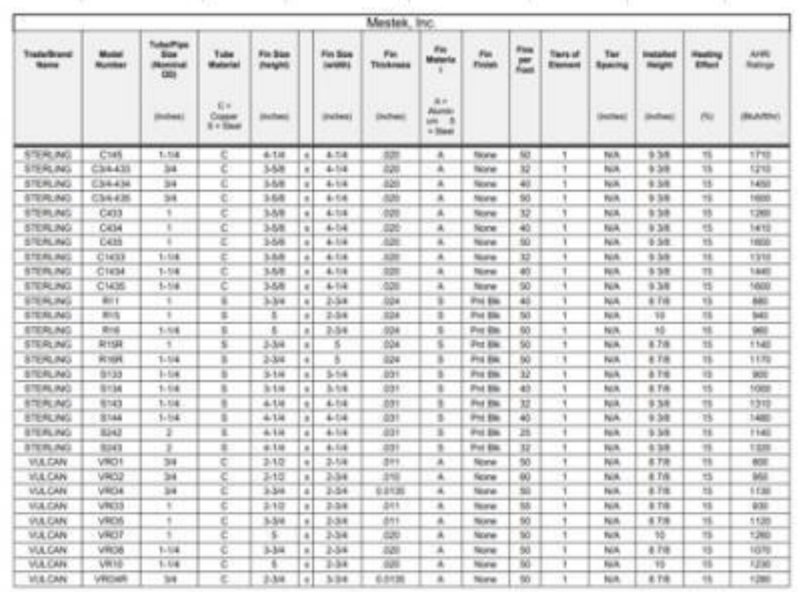
Space	Existing Radiation [Btu/hr]	Heat Load	Energy Balance	Proposed Radiation [Btu/hr]	Heat Load	Energy Balance	New Baseboard Needed Length [Ft]	AHRI Rating [Btu/hr/ft]	Output [Btu/hr]	New Energy Balance
Kitchen	5215.5	4668.8	546.7	1710	4668.8	-2958.8	18	950	3420	461.2
Study	4056.5	2092.5	1964.0	1330	2092.5	-762.5	9	950	1710	947.5

Adjust length of new baseboard and model to make energy balance non-negative

May want to match new energy balance to old (to ensure similar performance)


AHRI DIRECTORY OF CERTIFIED PERFORMANCE

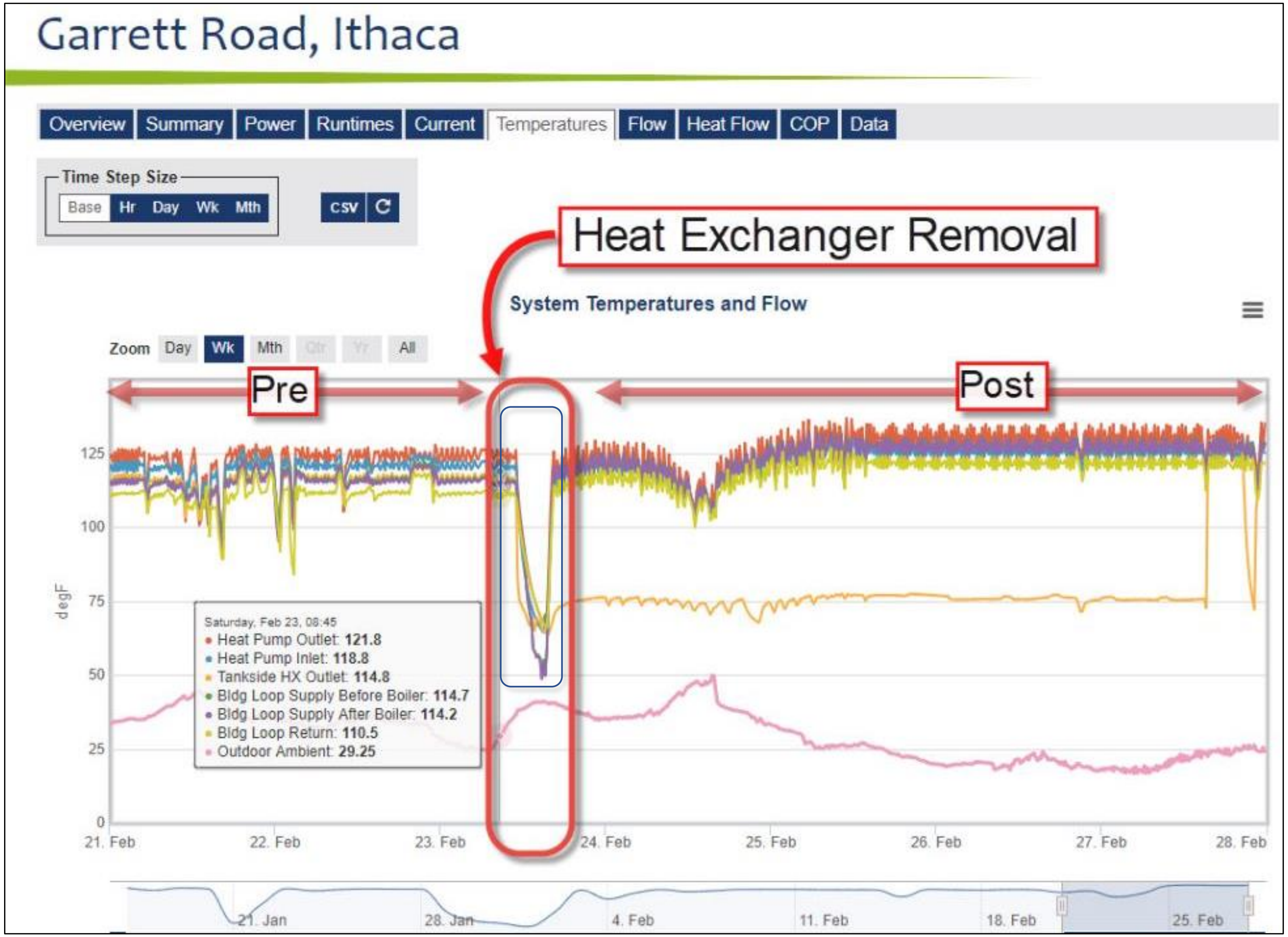
Mestek, Inc.


Mestek, Inc.

Source: http://www.ahrinet.org/App_Content/ahri/files/Certification/ComFinnedTube_AHRICertDirectory.pdf

Figure 57: Garrett Road – Operating Temperatures pre, and post-heat exchanger

M&V data provided by Frontier for the Garrett Road Site, showing system temperatures around alteration



Appendix B: Design Considerations

Design guidance for using air-to-water heat pumps based on our experiences conducting this demonstration project are included in this appendix.

New and Expected Air-to-Water Heat Pump Products

Several new heat pump products have entered the market over the duration of this project. Several more are expected to be released in the near future, and while we have not completed the same level of analysis and review of these models, it is worth noting their existence:

- Mayekawa - Model: HWW-2HTC
  - Water source heat pump that uses CO_2 as the refrigerant, similar to the Sanden SanCO2 (NOT an air-to-water heat pump).
- Nyle - Models: C25A, C60A, C90A, C125A, C185A, C250A
  - Air-to-water heat pump series, available with single phase power option. Major concern is that operation is limited to ambient temperatures above 40F, limiting heating use in New York climates.
- Colmac - Model: CxV Series
  - Potentially promising air-to-water heat pump. Output appears to drop significantly below 10F.
- Taco - Model: TBD
  - New air-to-water heat pump expected to be released in 2020.
- SpacePak - Model: TBD
  - New air-to-water heat pump model expected to be released in Q3 or Q4 of 2019. SpacePak is the distributer of the Solstice Extreme.
- Enertech - Model: TBD
  - Split system style air-to-water heat pump expected to be released in 2020.

Air-to-Water Heat Pump Considerations

All but one of the demonstration sites selected and installed a Solstice Extreme air-to-water heat pump. The remaining site installed a Sanden SanCO2 air-to-water heat pump. Despite this limited experience base, the following observed issues are common to both the Solstice and Sanden units.

- Poor documentation, complex control interface, and insufficient defaults: Multiple parties involved with the project noted that the unit controls and installation instructions were not very clear, nor sufficiently well-documented. All units required alteration of the default settings during installation to operate as desired.
    - Three of the five demonstration projects are owned by HVAC professionals, either design engineers or installing contractors, who are well-versed in mechanical systems. Even with the owners' background, installing and configuring the units to achieve optimal performance has not been a simple process. Alterations and adjustments to settings by the owners for system performance tuning continue at all of the sites, even those a year or more post-installation.
    - The manufacturers have not yet developed the necessary support network, and the technology lacks an adequately trained service industry or readily available replacement parts. On-call emergency service and same-day repair is not a realistic expectation for these systems.
- Integration with other systems: When used in tandem with a backup or supplemental heat source, the sequencing and control logic must be carefully thought out and implemented. This extends beyond digital control selection and involves the physical pipe layout and configuration of components. The design must ensure that the unit is receiving a suitably low entering water temperature, and that backup systems are not cycling on more quickly than the heat pump can react.
    - At this point, we do not consider any of the air-to-water heat pumps on the market to be ready for use as a solo heat source, so some form of backup and integration is necessary – note the observation above regarding availability of repair services.
    - It is less cost effective to install an air-to-water heat pump sized for the maximum expected load than to install a smaller heat pump for use 90% of the time with a less efficient backup source that runs the remaining 10% of the time during peak load conditions. All heat pumps experience reduced capacity and lower efficiency at low ambient temperatures, which is when the need for heat is greatest. While an air-to-water heat pump could be sized to handle peak loads plus a suitable factor of safety, the system would be greatly oversized compared with a non-heat pump heating system and the efficiency gains are limited.
- Design considerations with existing systems: When installed in an existing heating system, it is important to verify, and take steps to ensure, the flow rate and temperature drop through the system. Return water temperature plays a significant role in the unit efficiency and needs to be a key design consideration when installing one of these units. Sites that have existing systems with high flow rates and similar supply and return water temperatures will likely be difficult to adjust so that they are within a suitable range for heat pump operation. Sites which were not designed with low temperature

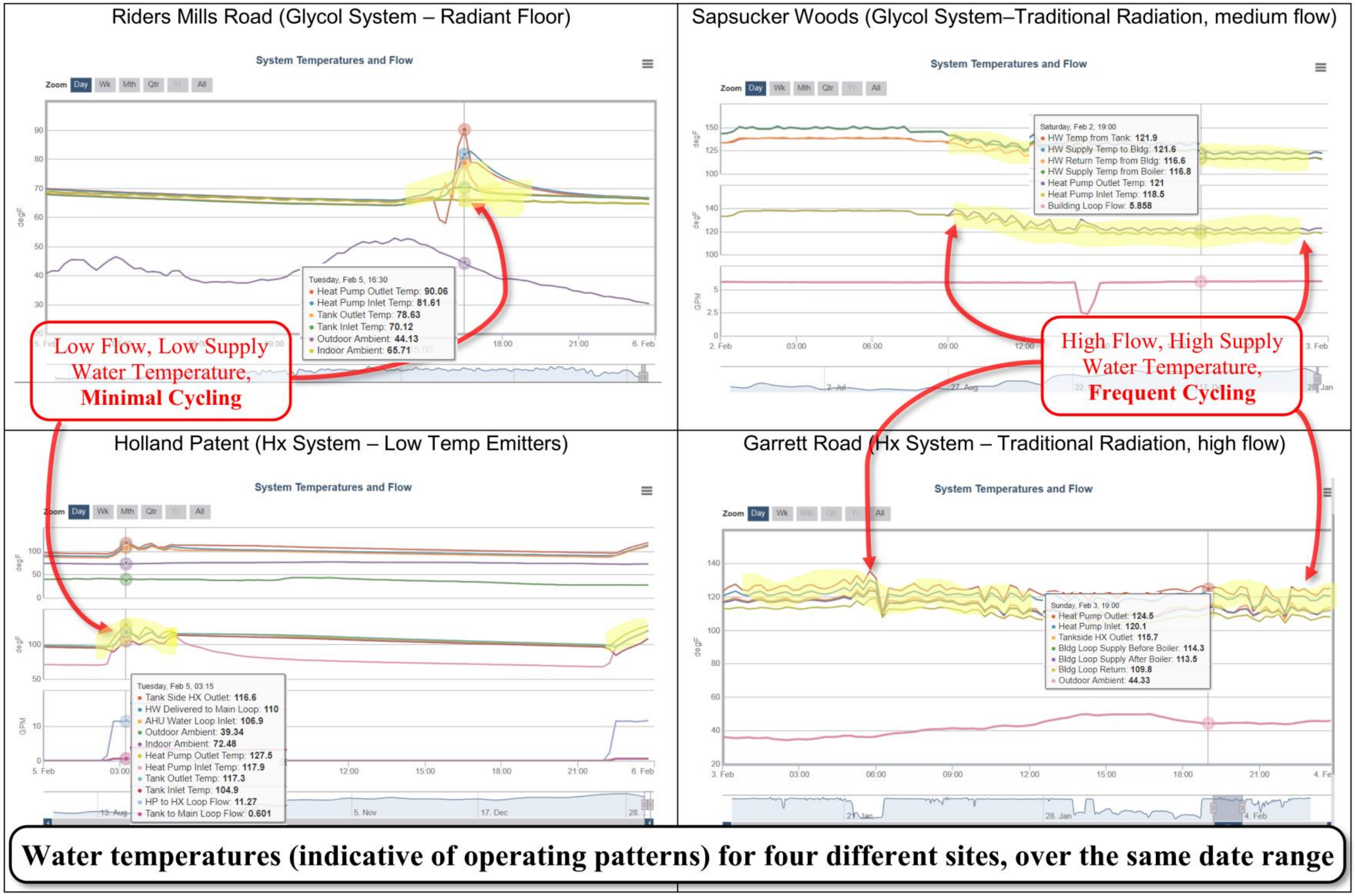
heat emitters showed noticeably more cycling than other sites, and they were less able to use the buffer tank as a heat storage system.

- For various reasons, hot water boiler systems are often thought about and designed around producing a fixed supply water temperature at full load conditions. This carries over to part load conditions, when a boiler will continue to deliver the desired supply water temperature, regardless of the entering water temperature. Some impacts of that are:
  - The amount of heat delivered to the space by the distribution system is determined not by the supply water temperature, but by the average water temperature of the supply and the return. Because we consider the supply water temperature to be fixed, or at least to have a maximum upper limit, one way to increase the average water temperature in a system is if the return water temperature is increased.
  - With a fixed supply temperature, the faster water moves through the distribution system, the warmer that average temperature will be, and the more uniform the heat output from the first and last heating elements in the system will be.
  - Many older systems with heat imbalances or issues with insufficient heat solved these issues by increasing the flow rate in the distribution system.
- With air-to-water heat pumps, the effect of increasing the distribution system flow rate on heat output is similar until the return water exceeds a certain point: 130F for the Solstice, and 122F for the Sanden. While the Solstice can supply water up to 140F, and the Sanden over 170F, if the return water temperature entering the unit exceeds their limit the unit will stop providing heat. At that point, by increasing the flow rate you are functionally limiting the amount of heat and maximum water temperature in the system by causing the heat pump to cycle off prematurely.
- An additional factor applicable to an air-to-water heat pump is the impact that high flow rates have on the buffer tank. Higher flow rates require a larger buffer tank. At a certain point, excessive flow will disrupt the tank stratification, minimizing its effectiveness.
- Return water temperature, flow rate and the difference between supply and return temperature play a significant role in the heat pump efficiency and should be a key design consideration.

With those caveats noted, a successful installation is certainly possible, and air-to-water heat pumps are generally rated for high efficiency operation. This technology is well situated to fill a niche for existing buildings with hydronic heating systems looking for a more efficient and fossil fuel free replacement. They have the potential to heat or pre-heat domestic hot water, something that differentiates them from air-to-air heat pump systems. They can be installed with significantly lower disruption and in a broader variety of sites than a geothermal source heat pump system.

Figure 58: Impacts of Flow and Cycling on HP Operation

A set of graphs showing temperature trends from four different sites.



Solstice Extreme Specific Considerations

Out of all the air-to-water heat pumps considered, the Solstice Extreme unit was the most well-developed system and had an operating range that was the most compatible with an existing hydronic heating system. However, the Solstice is not a mature product in comparison to non-air-to-water heat pump systems it is competing with. The controls and sequencing of the system in particular lacked the maturity of a seasoned product:

- We discovered a sequencing issue with the packaged Solstice controller that allowed the heat pump to begin running immediately after a programmed delay period without first re-checking the entering water temperature. When the backup heat was triggered on during this delay the heat pump would attempt to start at too high water temperatures, triggering a hard lock out condition.
- We also observed that the third-party controller used for the Solstice occasionally froze or otherwise deviated from expected operation. When this occurs, it needs to be manually reset.

Both these issues required owners to manually reset the unit before resuming normal operation. This is a simple process, but one that is beyond what would be expected of a typical owner. Although less of a concern to owners, we discovered that the factory default controls settings varied from one unit to another, which is undesirable from an installer perspective.

Sanden SanCO2 Specific Considerations

While only one Sanden unit was installed for this study, the product is also relatively well-developed due to its genesis as a domestic hot water heater. It is still clearly an emerging technology, and we encountered similar issues with the installation of the Sanden as those noted for the Solstice, with the addition of:

- Manufacturer technical support was very limited, and in some instances, it was discovered that the sales team had provided incorrect or incomplete information. Several of the operating limitations, such as limits on return water temperature, reduced capacity when used as a heating system, and mandated potable water use, were not divulged until after a site design had been completed and the owner had begun looking into purchasing a unit. This was disappointing since we made specific inquiries about any known limitations and also provided schematic drawings for feedback.
- Post-installation, the site had difficulty adjusting the unit so that it could deliver sufficient heat to the radiant floor slab. A radiant floor is a relatively good fit for this type of system, with low supply water needs, at around 90F for this site, and an thermal mass which supports the buffer tank to limit cycling. To provide the system with the full output capacity, the supply temperature was set to its maximum, approximately 170F. With that temperature supply water, the flow rates between the buffer tank and radiant floor, and buffer tank and outdoor unit had to be very carefully adjusted to deliver enough flow to transfer heat, but slow enough that the return water from the system remained below 120F. This provided a 50F drop, with all heat transfer to the slab crossing through the small manufacturer

specified Taco X-Block heat exchanger. This balance was accomplished at the demonstration site, but only with the support of flow and temperature sensors installed to monitor the demonstration project, and additional sensors that were installed and monitored by the owner. That level of metering and analysis is beyond what can be expected of a typical installation.

Figure 59: Sanden Flow, COP and Capacity

Excerpt from Sanden documents showing performance, capacity and flow rate possible for different entering water temperatures

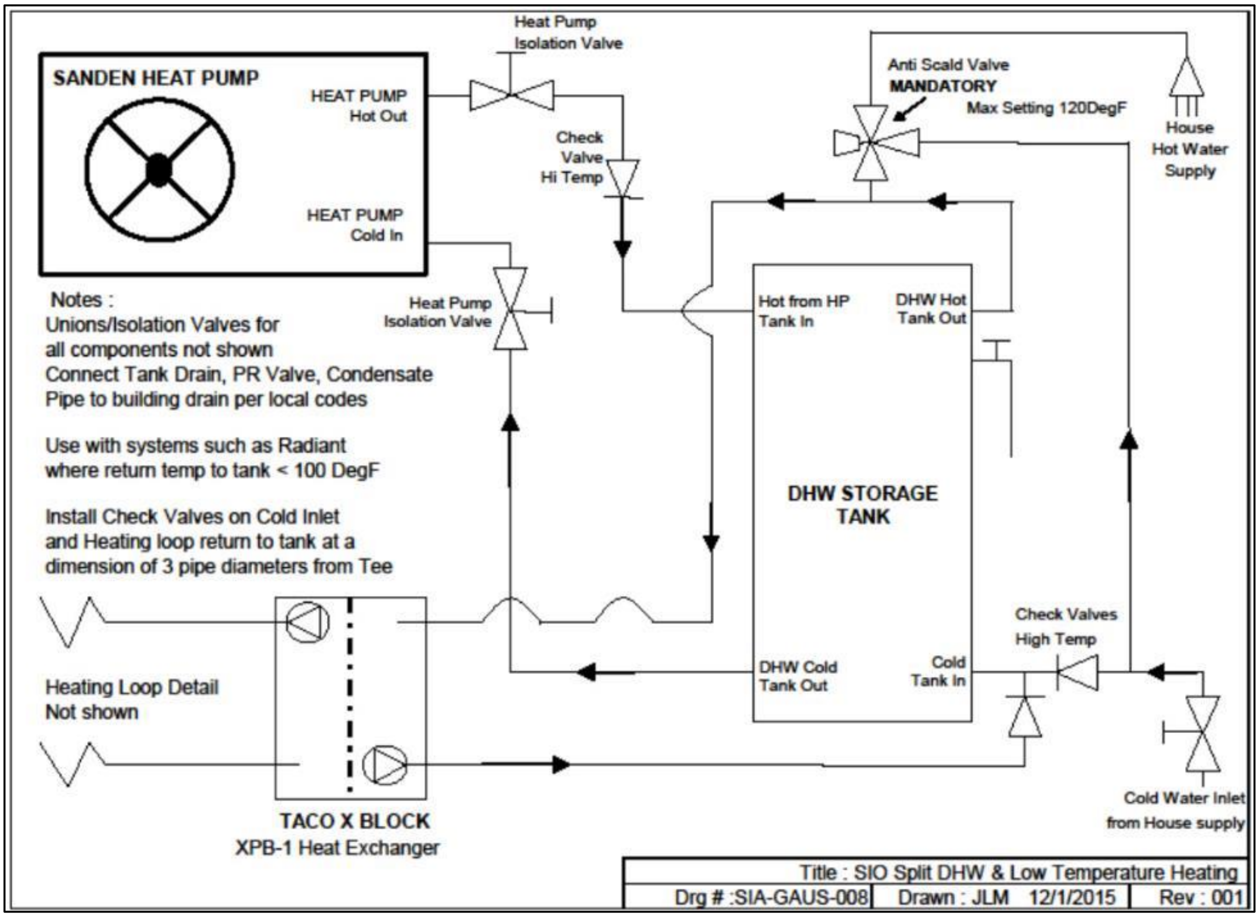
Range which is suitable for heating per Sanden

Inlet Water Temp °F	Unit Capacity (kw) / Btu/h	Unit COP	Flow Rate (GPM)
50	4.5 / 15,400	4.5	0.32
80	3.4 / 11,600	3.3	0.38
100	3.0 / 10, 200	2.7	0.45
115	2.6 / 8,900	2.4	0.49
120	2.4 / 8,100	2.0	0.58

- Controls adaptability is highly limited due to the required installation of a Taco X-Block combination heat exchanger and pump system. It should be noted that although this product works, and if it is run at steady state conditions, it will modulate its flow rate down low enough to pair with the 0.5 GPM rate passing through the heat pump. However, the default is to start both pumps at full speed and modulate down. Under low load conditions, this fully mixes the water in the buffer tank, and quickly brings the return water temperature above 130F, shutting down the system before the load is satisfied. This results in cycling, reduced efficiency and limited capacity.
- As a combination heating and domestic hot water system, with recirculation of the heating hot water, but not domestic hot water, the system must be carefully designed to avoid thermal expansion pressurization and/or pressure fluctuations. The manufacturer’s recommended installation does not adequately address this, and it results in a system which regularly ejects hot water from the buffer tank pressure relief valve. This is considered to be a part of normal operation for the system, according to the manufacturer.

Figure 60: Sanden Recommended Layout

Schematic drawing showing the manufacturer's recommended layout for the system



Buffer Tank Considerations

Buffer tank sizing and selection can have a big impact on the systems overall performance. A correctly sized buffer tank will enable the heat pump to operate more effectively by smoothing out peaks in load and decoupling the heat pump from higher speed and/or temperature distribution loops – similar to the buffering that occurs before viewing on online video to help ensure an uninterrupted viewing experience.

Buffer tanks should be sized based on expected loads and flow rate of the house side system at full and part load conditions, in combination with the rated flow needed by the heat pump. Larger tanks will cost more, and lose more heat through their surface, but they will allow the heat pump to run more efficiently, running longer at a consistent level and storing heat in the tank. A larger tank will allow the system to absorb temporary spikes in load, allowing short periods of greater than nameplate heating capacity.

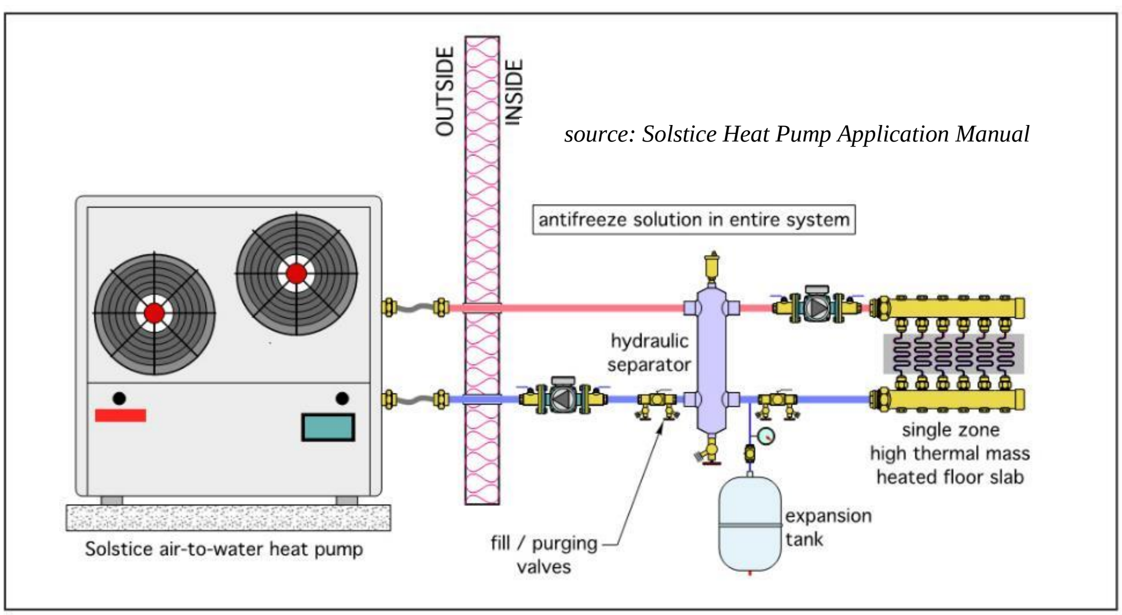
A variety of buffer tanks were investigated for this project, including tanks marketed by the heat pump manufacturer for use with their product, third party hot water storage tanks marketed for domestic hot water systems and buffer tanks for solar thermal systems with integral heat exchange surfaces.

When designing and installing the buffer tank, it is strongly recommended to use a primary-secondary approach to decouple the flow through the tank from the flow through the house side of the system. This approach means adding a pump, but it will help to control flow rates through the tank without significantly altering the flow rate through the existing distribution system and heat emitters. Keeping the flow low through the tank will allow it to act as an effective heat reservoir, preventing unnecessary mixing and maintaining stratification in the tank.

One exception, where a buffer tank is not required, is for new construction with high mass radiant floor which has been designed with an air-to-water heat pump in mind. In this instance the system can be designed with low flow rates and water temperatures that will allow the floor to act as a large buffer tank/thermal mass. If taking this approach, it is critical that there be hydraulic separation and that the flow rates be fully adjustable. The flow through the floor must be independent of the flow through the heat pump. This approach may not be suitable for all air-to-water heat pumps. It should be confirmed with the manufacturer and be part of an integrated radiant floor and hydronic system design.

Figure 61: Solstice installation without buffer tank in radiant floor application

Schematic of a Solstice air-to-water heat pump serving a radiant floor zone without the use of a buffer tank (replaced with a hydraulic separator).

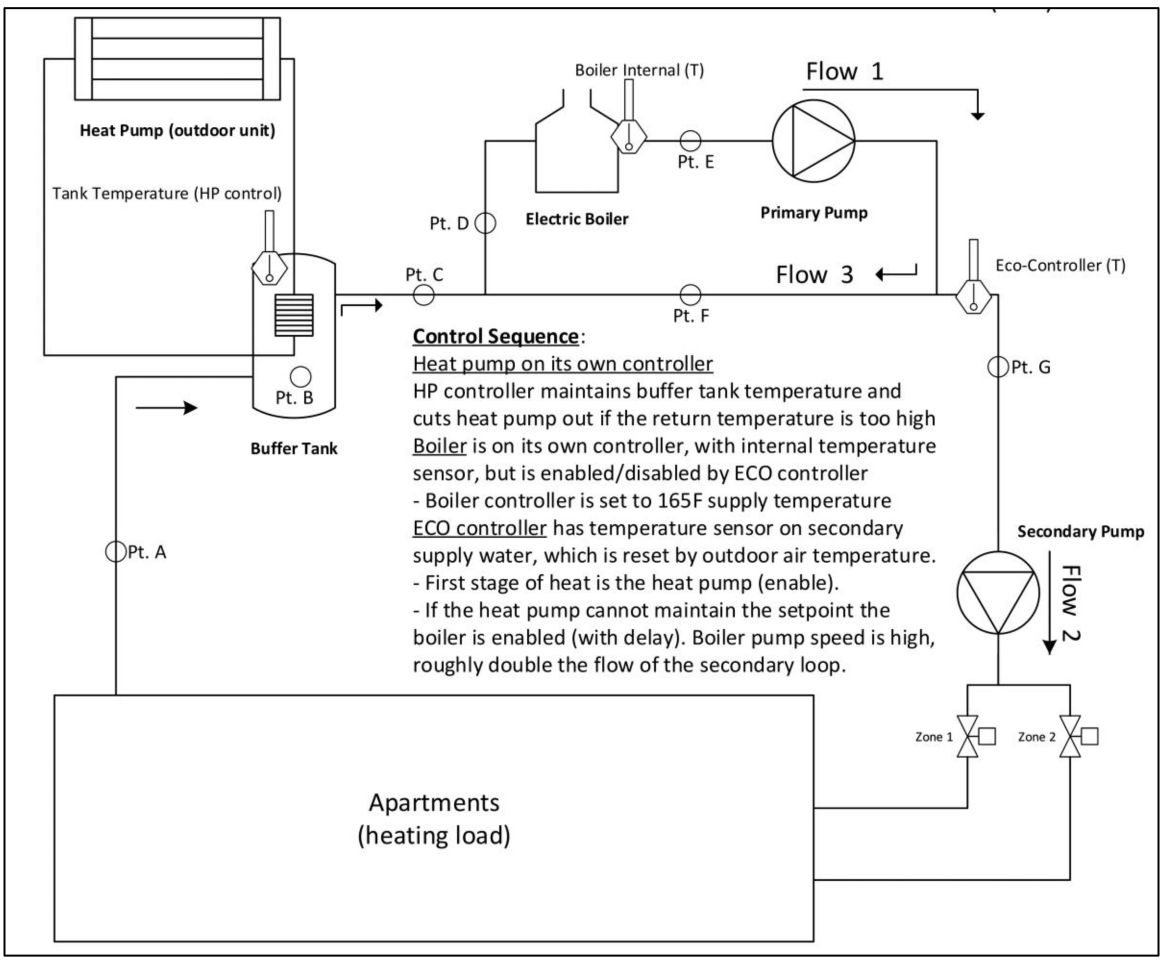


Controls and Backup Heat Considerations

A consideration when designing the system is the location of the backup heating system. This should be after the buffer tank to minimize the temperature of the water entering that tank and then returning to the heat pump. For existing systems with high flow rates, even this may not be enough to prevent a spike in hot water returning to the buffer tank, which can interfere with heat pump performance and cause unwanted cycling. It is important to consider third party controllers that allow more flexibility with delays before backup heat is engaged, or allow the backup heating source to modulate so during transition periods the heat from the backup system can be added to the distribution system without trigger the heat pump to shut down. This will allow the heat pump to operate longer and carry more of the heating load.

Figure 62: System layout with supplemental/backup heat downstream of heat pump buffer tank

Schematic layout from the Sapsucker Woods Road site, showing flow through the system elements



When integrating the heat pumps into existing systems, an additional controller was required to handle backup heating system staging, reset controls and multiple zone demands. While two of the sites opted to handle this level of control manually, it required going into the mechanical space to de-activate the heat pump, and open and close valves to engage the backup heating system. This is not the expectation for a typical homeowner.

The control system that we used that provided the most ‘set it and forget it’ experience to the owner was the Eco 550 controller. This was used at the Sapsucker Woods Road site, which had an offsite owner and needed the backup heat to seamlessly and autonomously cycle on and off when needed.

Figure 63: HBX Eco 550 controller details

System details from vendor (HBX)

Heat Pump & Backup Control

The ECO-0550 stand-alone control is designed to control equipment in a 2 pipe, single or dual tank, hydronic heating or cooling system. The ECO-0550 can control up to three (3) heat pump stages (air-to-water or water-water) or chillers and a reversing valve with outdoor temperature reset control.

This powerful control can also control a backup heat source (boiler) while operating two (2) heat pump stages. The backup heat source can be brought on with a few different options based on outdoor or tank temperatures. The control can manage single tank applications as well as applications with separate hot and cold tanks.

Heat Emitter Considerations

While some existing systems, particularly radiant floor, are suitable for use with low temperature hot water, we observed that most systems that were previously used with 180F supply water required adjustment, and in some cases, supplemental heat emitters. This was not always due to an inability to deliver the required heat, but sometimes a result of temperature imbalances caused by reducing flow rates which were noticeable at lower temperatures.

When adding supplemental heat to a system, it is important to consider the operation at low load conditions, full load conditions, and during backup (higher temperature) operation. Some pipe materials that can be used in radiant floor are not rated for the hotter water temperatures and must be protected if added to supplement a space.

When selecting supplemental heat emitters, the three primary considerations are: 1) cost 2) ease of installation, and 3) amount of heat produced. For spaces with accessible basements and suitable floor coverings, a radiant floor add-on may be the best option. Extending or adding to existing perimeter baseboard is often a relatively inexpensive option if wall space is available, or larger slightly more expensive multiple tiered baseboard can be added in select spaces. For locations where space is at a premium, convectors (often with a small fan or blower) can be added which have a higher first cost, but can deliver more heat from a smaller footprint than other options.

Figure 64: Side-by-side visual for various heat emitters

Radiant Floor (or alternate radiant wall/ceiling approaches)	Traditional, Low-temperature or multi-tier baseboard solutions (including panel radiators)	Combination radiation and convection solution.