RCC Pilot Project: Multifamily Heat Pump Water Heaters in Below Grade Parking Garages in the Pacific Northwest

ECOTOPE

Prepared for:

The Bonneville Power Administration (BPA):
Emerging Energy Efficient Technologies Program (E3T)

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Executive Summary

This is the final report on two pilot installations of Reverse Cycle Chillers (RCC) for domestic hot water production in multifamily buildings in Seattle WA. The RCCs are commercial air-cooled chillers setup as heat pumps to create hot water. The RCCs are installed in below grade parking garages to take advantage of the earth buffering and mass effects to maintain warmer entering air temperatures throughout the year.

The buildings were completed and fully occupied in 2013 and 2014. Measurement and verification (M&V) submeters were installed and used to monitor system performance during the early periods of occupancy. Data from these meters allowed for diagnosis of problems and adjustments to the design to improve the functioning of the heat pumps. The primary findings and conclusions are as follows:

- The parking garages are providing significant performance benefits for the heat pumps by maintaining relatively high temperatures throughout the year (average 64-68ºF). The temperature in the parking garages did not drop below 48-50ºF. This indicates that the heat pumps can be used to provide water heating year-round in this climate without the need for back-up heat sources.
- The RCCs are achieving an average annual COP of about 2.4-2.8 installed in the parking garages.
- About 30-45% of the energy supplied by the heat pumps escapes from the storage, distribution, and recirculation piping before it is used at the hot water fixtures. However, the total amount of energy loss is not significantly different from the losses to be expected with individual electric tanks in the units. Furthermore, some of these losses offset space heating from electric resistance heaters.
- The system COP represents about a 260% improvement in efficiency when compared to electric resistance water heating. The RCC system uses about 38% of the energy used by an electric resistance water heating system (central boiler or water tanks in the units).
- Including heating system interaction in a building heated with electric resistance space heating the RCC results in about an 18% reduction in the total energy use of a typical new mid-rise multifamily building in Seattle.
- Industry and code standard practice calculations for water heater capacity, storage volumes, and pipe sizing overestimate the hot water demand that we actually experienced at the pilot buildings.
- Heat pump efficiency is closely correlated with incoming water temperature. Recirculation water can significantly increase the average water temperature delivered to the heat pumps and reduce efficiency of the entire system. New designs must take this into account.
- Measurement and verification (M&V) equipment was essential to diagnosing and allowing for optimization of the system. M&V equipment should be included on any emerging technology project.
- If back-up heating is used it should either require manual intervention to switch it on, or there should be an automatic alarm that alerts maintenance personnel when there is a heat pump failure.

Introduction

In 2009 Ecotope completed a feasibility study for the Bonneville Power Administration (BPA) Emerging Energy Efficient Technology (E3T) program.[1] The study examined the use of Reverse Cycle Chillers (RCC) to produce domestic hot water for multifamily buildings in the Pacific Northwest. An RCC is essentially commercial chiller technology set up to operate in reverse as a heat pump water heater and equipped with a double-walled copper heat exchanger so that it can process potable water directly. The RCCs used contain R-134a refrigerant which does not function well at very low supply air temperatures. The innovation in this study was to take advantage of the thermal buffering effects of below grade parking garages to allow the use of this R-134a heat pump technology year-round for the production of domestic hot water in the Pacific Northwest climate.

Following the feasibility study two multifamily building projects in Seattle were recruited for pilot projects. In addition to support for the pre-design work carried out in the feasibility study, BPA provided funding for system commissioning, coordination with the local utility (Seattle City Light) for conservation incentives, and for a Measurement and Verification (M&V) study.

Although the pilot buildings were recruited in 2009 and 2010, due to the failures in the banking industry and subsequent recession in the building industry around that same time, the first pilot was not completed until autumn 2013 and the second was not completed until the autumn of 2014. Measurement and Verification data allowed for a number of issues to be identified and corrected in the first pilot project and also led to design changes in the second pilot. A earlier draft report that presented results of the first case study preceded this report in the fall of 2014. This report presents findings from the pilot projects. It includes discussion of recruitment and design, lessons learned, and results of data analysis[2].

Figure 1: Stream Uptown Apartments – The first RCC Pilot project to be completed.

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[1] Reverse Cycle Chillers for Multifamily Buildings in the Pacific Northwest: Phase I Final Report. Jonathan Heller and Carmen Cejudo, Ecotope Inc. September 2009. Produced for the Bonneville Power Administration.

[2] Jonathan Heller and Shawn Oram. *RCC Pilot Project Report: Multifamily Heat Pump Water Heaters in Below Grade Parking Garages in the Pacific Northwest – Draft Report*. November 7, 2014. Prepared for the BPA E3T program.

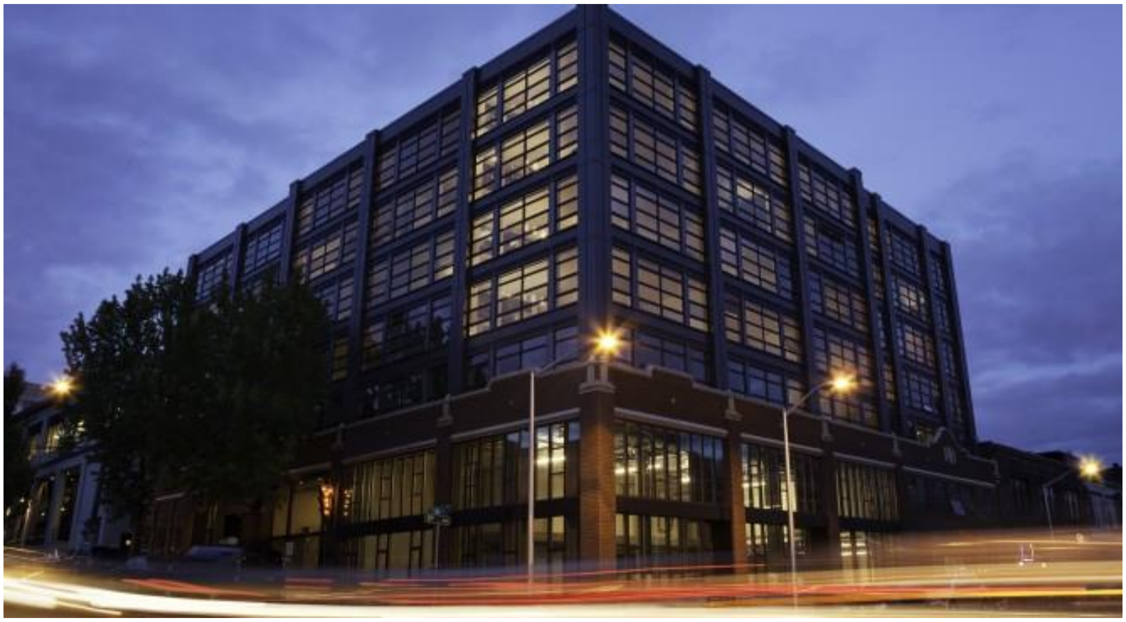

Figure 2: Sunset Electric Apartments – The second RCC Pilot project to be completed.

Pilot Recruitment

Using RCCs to create hot water in multifamily buildings leads to potentially large energy savings compared to a base case multi-family design of electric tanks in each apartment unit. These energy savings are reflected in energy models and “Energy Points” for third party sustainability rating systems such as LEED.[3] This provides a significant incentive for projects seeking to achieve higher levels of certification (i.e. LEED™ Gold or Platinum) for market differentiation. Seattle City Light was also willing to provide significant rebates to encourage the use of this type of technology. These two factors along with the additional support offered by BPA to ensure adequate integration of this innovative system enabled Ecotope to convince project developers to use the RCC system and take part in the pilot.

The *Sunset Electric* project was recruited in 2009 but put on hold due to the banking and housing market problems of 2008-2012. It was eventually sold to a new developer and was completed in 2014. It is a 92-unit multifamily building in the Capitol Hill neighborhood of Seattle. It is 6-stories tall and includes 1.5 levels of below grade parking.

The *Stream Uptown* project was recruited in 2010 and temporarily put on hold, but completed in early 2013 and fully occupied by autumn 2013. The project includes 118 apartment units, is 6-stories tall, and includes a single level of parking that is about 75% below grade. Ecotope convinced a third project, *Stackhouse*, to incorporate RCCs, but they did not negotiate participation in the pilot. That project was completed in autumn 2013 and is fully occupied. It is 215 residential units in 7 stories over 2.5 levels of below grade parking. No separate M&V was conducted on this system, but billing data indicate that the overall building is extremely energy efficient at about 5.9 kWh/SF-yr.

[3] LEED™. Leadership in Energy and Environmental Design. US Green Building Council.

Design Development

The original design for the water heating and storage plant was developed with the assistance of Colmac Industries in Colville, WA. Colmac has been marketing RCCs for domestic water heating in hotels and hospitals in Hawaii and other hot humid climates for a number of years. They had developed a methodology for set-up of the heat pump controls and storage that works for their warm climate customers. Since this had been developed and tested in the field, we based the design of the first pilot on those existing system designs. The schematic design for this system is shown in Figure 3.

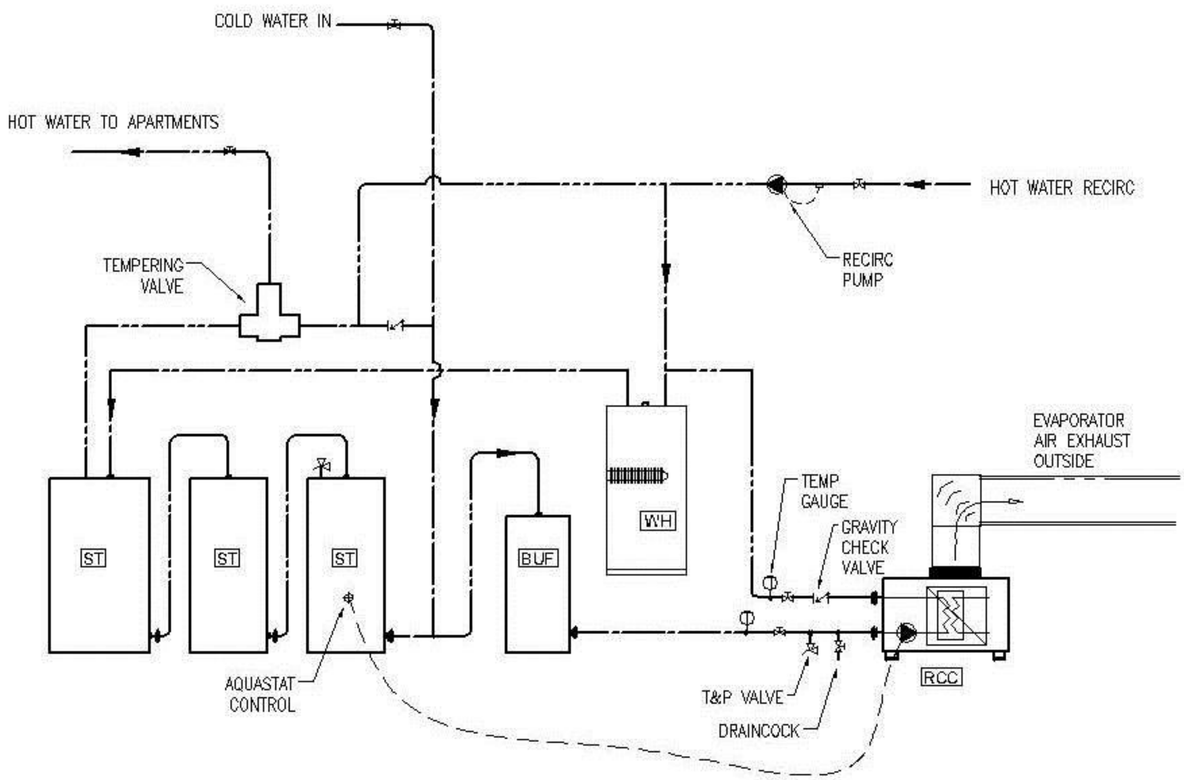

Figure 3: Simplified Initial Schematic Concept

Critical features to this design concept include:

- Single Pass: The design is based around a "Single Pass" pumping strategy as opposed to the typical "Multi Pass" strategy employed in most hydronic space heating applications. This means that the flow of water through the heat pump is regulated by a control valve to maintain a target output temperature of 130-140ºF. This results in a variable flow rate and variable temperature rise across the heat pump as opposed to the typical fixed flow rate and fixed 10-20ºF temperature rise on the water. The heat pump can therefore output 140ºF water with incoming water temperatures ranging from 45-110ºF.[4] The advantage of the Single Pass arrangement is that a usable water temperature is always delivered to the top of the storage reservoir.
- Multiple Storage Tanks: This design is based around the use of multiple smaller storage tanks plumbed in series. The series plumbing arrangement enables a high degree of temperature stratification throughout the system with the hottest water at the end of the storage system where water is sent to the apartments. It also allows the use of smaller cheaper tanks that are easier to install.
- Storage Temperature: The water is produced at a relatively high temperature (~140ºF) in order to control possible legionella bacteria and it is tempered to 120ºF before delivery to the apartments to avoid scalding.
- Cold Water Buffer: This design includes a cold water buffer tank immediately upstream of the RCC. This is meant to ensure that the RCC always receives cold water to avoid high pressure faults in the refrigeration circuit and achieve the highest possible coefficient of performance.
- Electric Resistance Back-up Heat: A tank with an electric element is included in the circuit immediately downstream of the RCC. This heater is set to maintain 125ºF water. Since the RCC is designed to output 140ºF water, the electric tank is intended to operate only if the heat pump cannot keep up with the load.
- Ring Main Heater: The electric resistance tank is also intended to make up the heat loss associated with the recirculation loop or "ring main". This was done to avoid bringing hot recirculated water back to the heat pump and risk high limit issues.
- Controls: The RCC is set to switch on when the aquastat in the first storage tank drops to about 115ºF and stay on until the aquastat rises to about 120ºF.

Stream Uptown Design

The first of the pilot projects to begin construction was the *Stream Uptown* building in the Seattle Center neighborhood of Seattle. In many ways the garage at this particular site represents a "worst case" test of the RCC concept. The garage is relatively small having space for only about one car per every two apartment units. It is a single level and is not fully below grade with about 4 feet of exposed concrete wall

[4] If the incoming water to the heat pump is much hotter than about 110F the flow is not adequate to remove all of the heat generated by the refrigeration cycle and the refrigerant pressure will rise and shut the system down on a high limit control.

above grade. Furthermore, there are 12 small air-to-air heat pump units mounted in the garage extracting heat in the winter to provide heat for the apartments and amenity spaces above.

Ecotope designed the water heating plant while the rest of the plumbing in the building was delivered by a design-build contractor. Based on the ASHRAE sizing calculations for service hot water to an apartment building of this size[5] we used two 15-ton RCCs and 800 gallons of storage. The system was designed as two parallel heat plants; each of two heat pumps with three hot water storage tanks, a cold water buffer tank, and an electric water heater. The storage tanks were delivered preassembled on a skid provided by the same equipment distributor that provided the RCCs.

Figure 4: Stream Uptown Hot Water Storage Tanks on two sides.

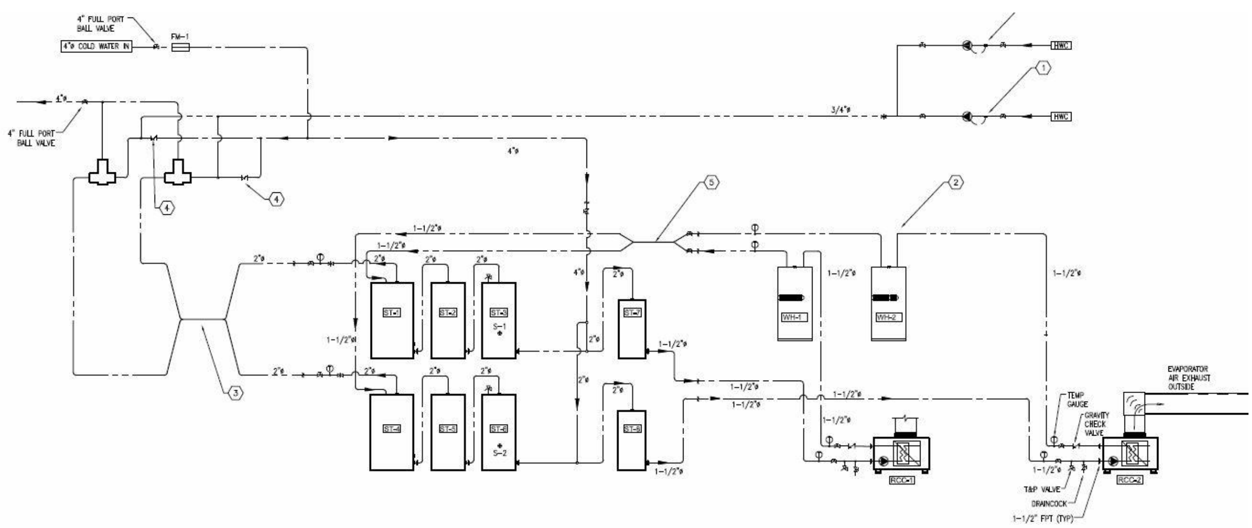

Figure 5: Stream Uptown Design Schematic

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5 2011 ASHRAE Handbook of HVAC Applications. Chapter 50. Figure 21.

As this was the first installation of this type, factors related to the equipment, the installation, and the design contributed to initial difficulties getting the system to perform as expected.

Equipment Issues

- The plumbing skids were piped up with the aquastat at the same level as the incoming cold water inlet. This led to short cycling of the heat pumps whenever there was a small amount of water used. See Fig. 6.
- The RCCs were not initially set up with the proper defrost programming which led to high limit failures when ice formed on evaporator coils.
- The heat pump manufacturer did not implement the control logic needed to allow for the electric back-up to work in the event of a heat pump failure. When there is a failure in the heat pumps the design intent was for the heat pump circulator pumps to continue to function and for the flow valve to open.

Figure 6: Stream Aquastat Location

- The tempering valves installed on this project were non-electric thermostatic valves which do not function well with low water flow and varying input water temperatures. Further, they do not function well with a relatively low temperature difference between the inlet hot water temperature and the target outlet temperature. This led to fluctuating supply water temperatures.

Installation Issues

- The expansion tank was installed on the wrong side of a check valve so that the hot water storage tanks were not protected. This contributed to leaking at the tanks and the water flow meter.
- The hot water storage tank skid installation was not thoroughly coordinated and when it came time to install the skid in the garage, a waste piping stack ended up being in the way of the skid piping which required the skid to be rotated 180 degrees from original design.

Design Issues

- The recirculation pumps selected by the plumbing contractor had a high flow rate (two at 12-17 gallons per minute each). Furthermore they were initially designed to run continuously. This is significantly more flow than the pumps in the RCCs which led to mixing problems in the hot water storage tanks.
- The recirculation loop was plumbed back to the electric resistance tank with the intent that the electric resistance heat would make-up the recirculation losses. However, the recirculation loop was returned to only one of the hot water tanks leading to an unbalanced flow between the two sides. Furthermore, since the flow rate from the recirculation pumps is quite high, the electric resistance was running to heat all of the recirculated water to 125ºF and filling the entire bank of storage tanks with water heated by the electric resistance elements. Simply put, the electric elements were running much too often and compromising the overall efficiency.
- The tempering valves selected by the plumbing engineer were significantly oversized. Two parallel tempering valves were used; each with a capacity of 5-200 GPM. The peak flow rates recorded by the flow measurement equipment during the first 6 months were less than 30 GPM. Flow can be as low as 0.5 GPM. These tempering valves do not work well at or below the low end of their specified range nor do they respond well to fluctuating hot water sources.
- Overall the hot water plant and water distribution system were significantly oversized. The sizing was based on industry standard equations that are based on typical apartment usage for standard plumbing fixtures. This is significantly higher than the actual demand observed in this building. The plumbing fixtures and appliances use substantially less water than "standard" fixtures especially since these buildings emphasized the use of low flow shower heads and other fixtures. Furthermore most of these apartments are small studios for single young professionals who do not appear to use as much hot water as the industry standard equations suggest. Oversized pipes, tanks, heat pumps, and valves lead to less control, ghost flows in piping, and high losses.

Various improvements were made over the course of the first 6-months of system operation to remedy the above problems.

- The expansion tank was moved to the correct side of the check valve and a second tank was added for additional capacity.
- The defrost programming was correctly implemented in the RCCs.
- The recirculation pumps were replaced with variable speed constant pressure pumps controlled from aquastats so that they run until return water rises to 110ºF and turns on when return water drops below 100ºF.
- The recirculation loop was re-piped to return to the storage tanks rather than to the electric water heater.
- The water piping entering and leaving the storage bank has been piped together to balance the flow through the two sides of the system.
- The heat pumps and flow control valves were reprogrammed to allow the pumps in the RCCs to run if the compressors are down to allow for the electric resistance element back-up function.

- One of the parallel tempering valves was removed and replaced with an electronic digital mixing valve which can reliably operate at varying flow rates and variable hot water source temperatures. The other non-electric valve was shut off.
- Refrigerant charge was reduced to allow for higher return water temperatures to enter heat pumps without triggering high head pressure alarms.

Sunset Electric Design

The second pilot project to begin construction was the *Sunset Electric* building in the Capital Hill neighborhood of Seattle. This project built a 6-story new mid-rise apartment building within an old historic façade. The RCCs are located in the below grade parking garage. This garage is also relatively small and not ideal thermally in that the building design includes a large central courtyard, so the center of the parking garage is not under a heated building.

Figure 7: Sunset Electric RCC System During Construction

Once again, Ecotope designed the water heating plant while the rest of the plumbing in the building was delivered by a design-build contractor. The equipment design here was nearly identical to the Stream Uptown project. The configuration of the storage tanks and electric water heaters was changed somewhat to reduce the amount of electric resistance heating and improve control over the heat pumps. A schematic of the final design is shown here in Figure 8.

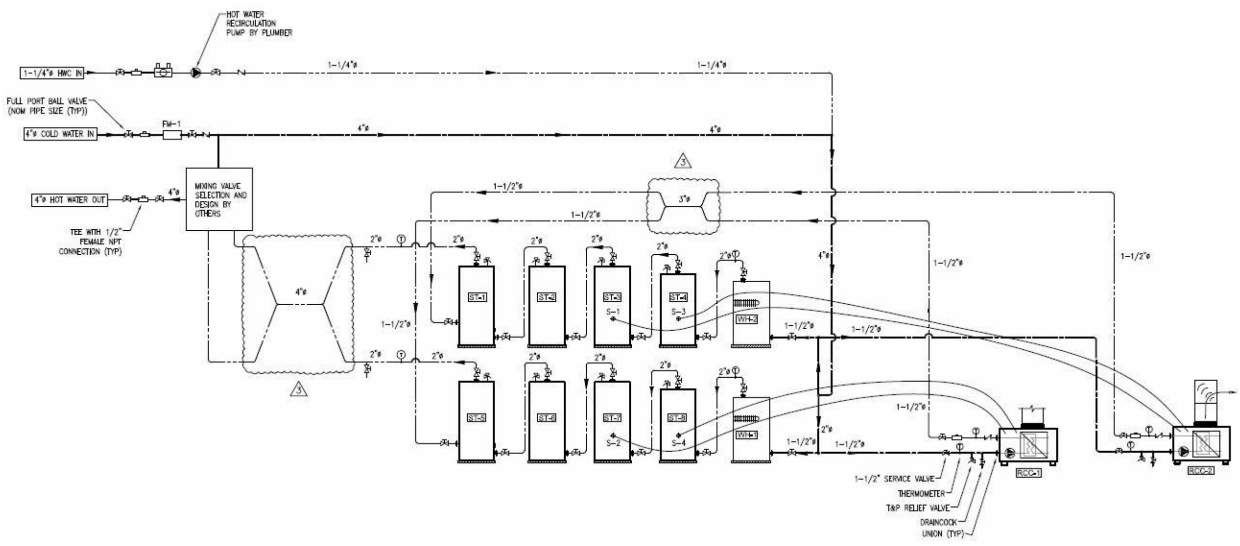

Figure 8: Sunset Electric Design Schematic

Again, several factors related to the equipment, the installation, and the design contributed to difficulties getting the system to perform as expected.

Equipment Issues

- One of the RCCs lost refrigerant charge due to a leaky part.
- The compressor in one of the RCCs broke and was replaced on warranty.
- Both units were overcharged with refrigerant leading to nuisance high head pressure alarms.
- Discharge pressure transducer on one unit failed and was replaced.
- Control settings took time to get programmed correctly.

Installation Issues

- Hot water circulation was initially inadequate to maintain hot water throughout the distribution system leading to multiple complaints of lack of hot water in the building.

Design Issues

- The hot water plant was significantly oversized. The occupants in the Sunset Apartments use even less water than the occupants of the Stream Apartments. Very low water use leads to short cycling of the heat pumps to maintain the circulation loop temperature.

Various improvements were made over the course of the first 6-months of system operation to remedy the above problems.

- Flow controls were opened up in the circulation loop to increase the water flow and raise water temperature delivery throughout the building.
- Refrigerant charge was reduced to allow for higher return water temperatures.
- Half of the storage was valved off and only one RCC is used at a time to more closely match the equipment output to the load.
- Controls were added to automatically switch from one RCC to the other in a lead/lag configuration. Each RCC is cycled as the lead RCC for 1-week. If there is a failure in the lead RCC the lag RCC is automatically brought on line.

Measurement and Verification

Data was collected with the intent of enabling diagnosis of operations, tracking usage, and calculating overall performance of the systems. The data points collected include:

Figure 9: Flow Measurement Devices

- Water temperature sensors for incoming cold water, tempered hot water supply to the apartments, and hot water output temperatures from each RCC;
- Air temperature and relative humidity (RH) sensors for garage air temperature and outside air temperature;
- Current transformers for heat pumps and for electric resistance back-up heaters;
- Flow totalizer for cold make-up water feeding hot water storage tanks.

- At the Sunset Electric project "Btu-meters" [6] were added to directly measure heat produced by the RCCs. This allowed for a direct calculation of actual performance of the RCCs as a Coefficient of Performance (COP).

Initially we had planned to use strap-on water temperature sensors on the copper water pipes. However, after some effort, it was determined that we were not able to get accurate temperature readings with strap-on technology. We therefore switched to wet-well immersion type sensors that the plumber installed in the lines.

We also had significant trouble getting an accurate reading of outdoor temperatures due to solar and other thermal effects around the buildings. At Stream we constructed an aspirated temperature sensor requiring a new penetration through the North side of the building but, even with this apparatus, the temperature signal fluctuates widely. We therefore determined to use the data stream from a nearby weather station for our outdoor temperature data point.

Output graphs of the temperature, flow, and energy use data were used to diagnose issues with the functioning of the system and determine performance.

Figure 10: Hot water temperature sensor

[6] Btus cannot be directly measured. A Btu-meter is actually a combination of a flow meter plus two temperature sensors. Btus are then calculated based on volume flow times temperature change times density and specific heat assumptions.

Stream Uptown Monitoring

A graph showing the performance of the Stream Uptown system from the time it was installed until the end of October 2014 is shown in Figure 11.

- *Gallons per Minute* is the average consumption of hot water during the measurement interval,
- *Garage Temp* is the air temperature in the garage,
- *Cold Water Temp* is the entering water temperature from the city,
- *Hot Water Temp* is the temperature delivered to the apartments after the tempering valve,
- *Outdoor Air Temp* is the average outdoor temperature,
- *Heat Pump Energy* is the KWH consumed by the RCCs,
- *Resistance WH Energy* is the KWH consumed by the electric resistance water heaters,

Also shown at the top of the graph is the total hot water consumed and electricity used by the heat pumps and electric resistance water heaters during the period shown.

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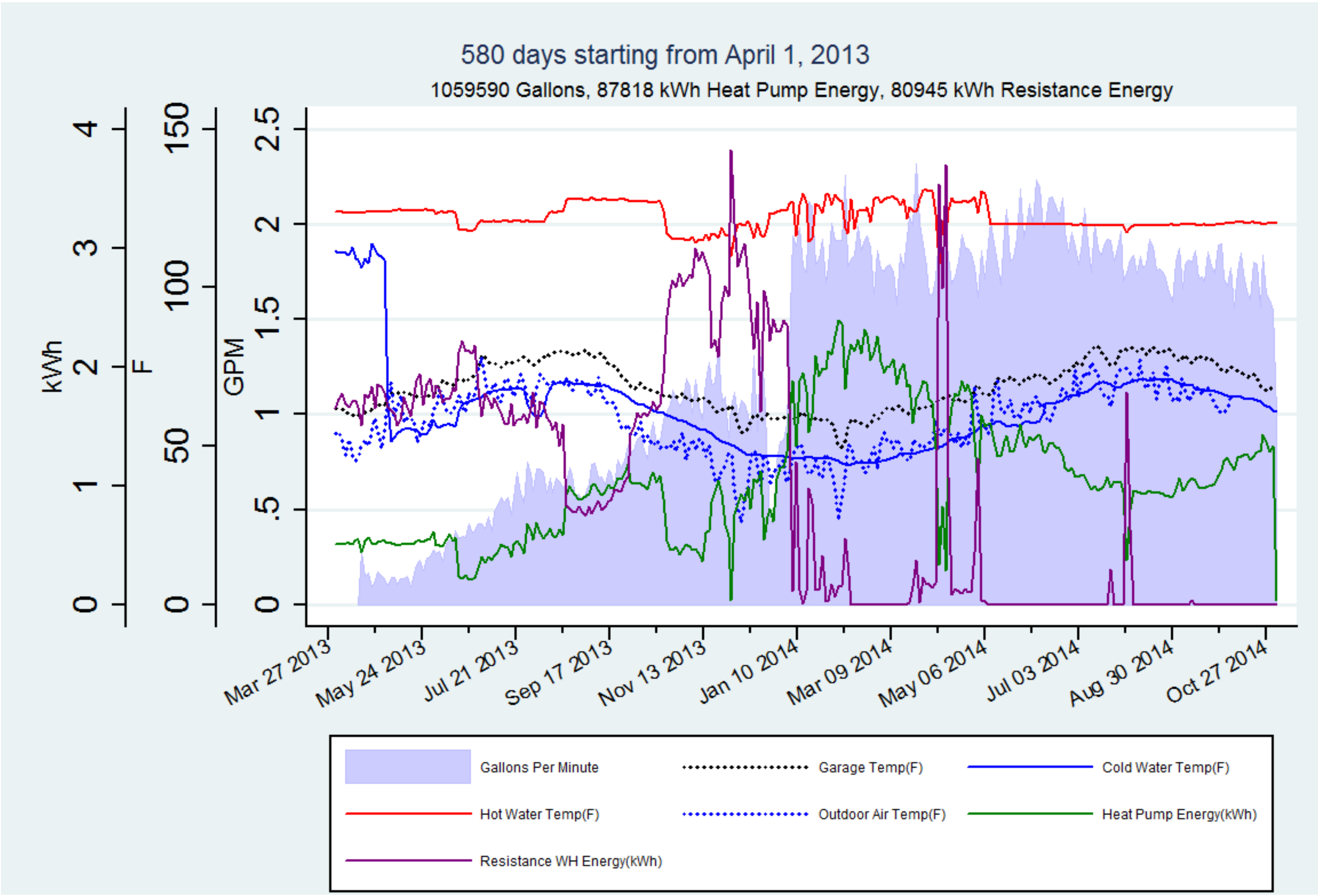

Figure 11: Long-term Data for Stream Uptown RCC Performance

A number of interesting things can be seen from this overall picture of the history of this project:

- First, note the background shaded blue data representing the average flow rate of water into the water heating system. It can be seen that during 2013 the building was slowly being filled with tenants and full capacity (full daily water usage) was reached at the beginning of 2014.
- Per our original design hypothesis, garage air temperature is shown as very effectively buffered by the below grade parking garage per the original hypothesis. The average daily temperature in the garage ranges from 48-82ºF; consistently warmer than outdoor temperatures.
- The graph also shows the typical seasonal swing in incoming water temperature, from 44-71ºF. This swing has a large impact on the seasonal energy use of water heating systems, needing about 50% more energy in the winter compared to the summer to heat the water to a usable temperature.
- The red line near the top of the graph is the supply water temperature to the apartments. It can be seen that early on when the building was not fully occupied the system was able to provide stable supply water temperatures. After the building was fully occupied, and we began making changes to the controls and piping configuration, the delivery temperature was variable. After the final repairs and installation of the digital tempering valve (spring of 2014) the water temperature has been remarkably steady.[7]
- The purple line represents the energy used by the electric resistance. The original design with the recirculated water returning to the electric tank resulted in large amounts of electric resistance usage. After the final design revisions it can be seen that the electric resistance is essentially off.

Figures 12-15 on the following pages show data from four distinct time periods in more detail:

1. The first period shows that one of the RCCs was running and the other was not functioning. The residents were getting hot water, but most of the energy was being supplied by the electric resistance due to the routing of the recirculation loop into the electric tank and the high pumping rate of the recirculation pumps pushing large quantities of water out of the storage tanks and through the electric tank.
2. The second time period shows after the piping was changed to reroute the recirculated water back through the storage tanks. Note that the heat pumps are supplying all of the heat to the system, but the delivery water temperature is dropping overnight due to too wide of a differential in the aquastat setpoint (the temperatures that turn the RCCs on and off).
3. The third graph shows the system functioning after the controls problems were fixed and a thermostat was added to cycle the recirculation pump. Note that the RCCs are supplying all of the heat to the system; the electric resistance heaters are not needed, and the water is staying between about 110-130ºF, but is still fluctuating due to the poorly operating non-electric tempering valves.
4. The final graph shows the system operation after the replacement of the recirculation pump with a variable speed pump and the tempering valve was replaced with a digital mixing valve. Note that the RCCs are cycling as expected, the water temperature delivered to the building is steady and there is no use of the electric back-up heat.

[7] The short period of cooler water and electric resistance usage shown is related to a brief power outage at the site associated with some nearby construction. The heat pumps had to be manually reset.

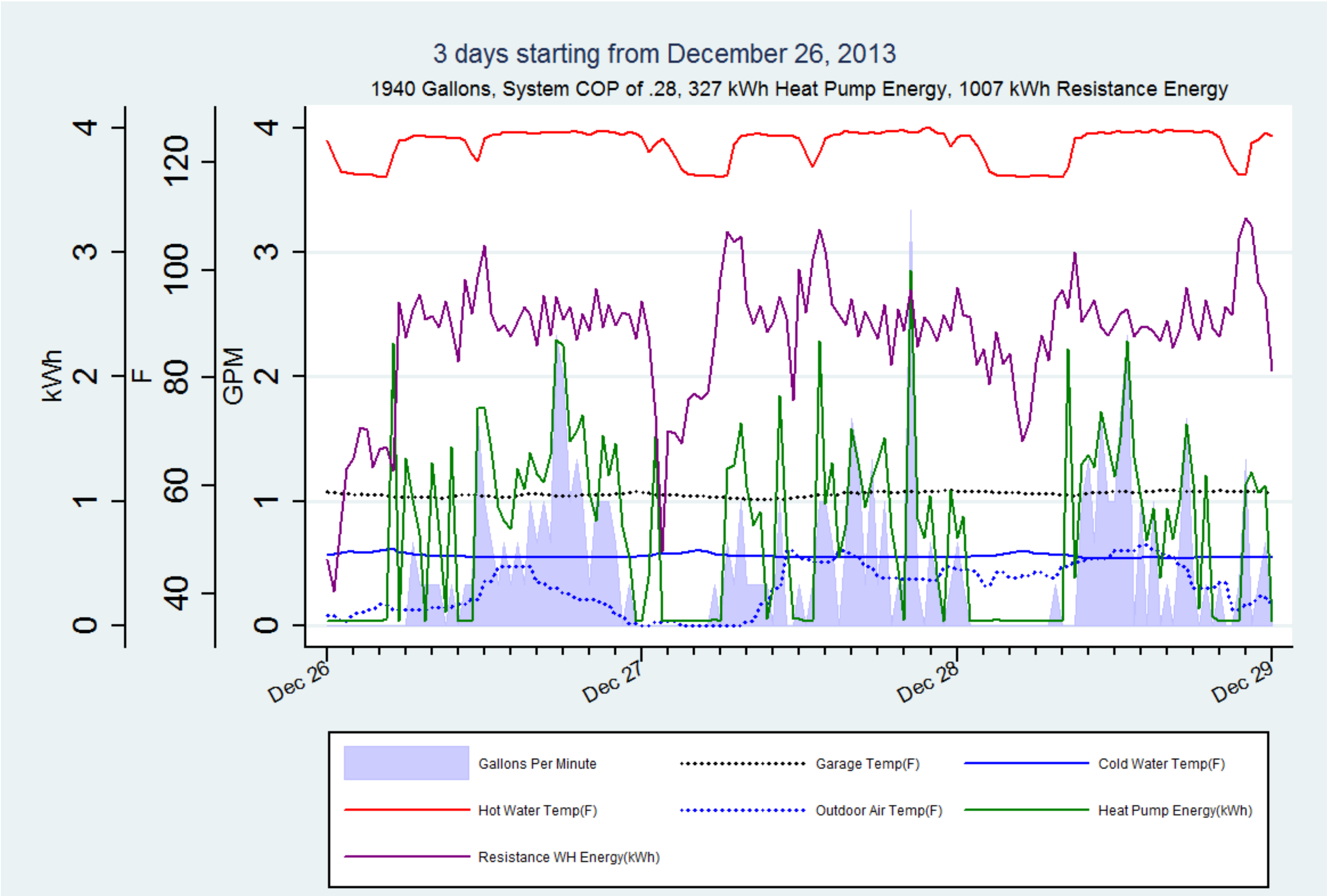

Figure 12: Sample of Early RCC Performance with Electric Tanks Operating

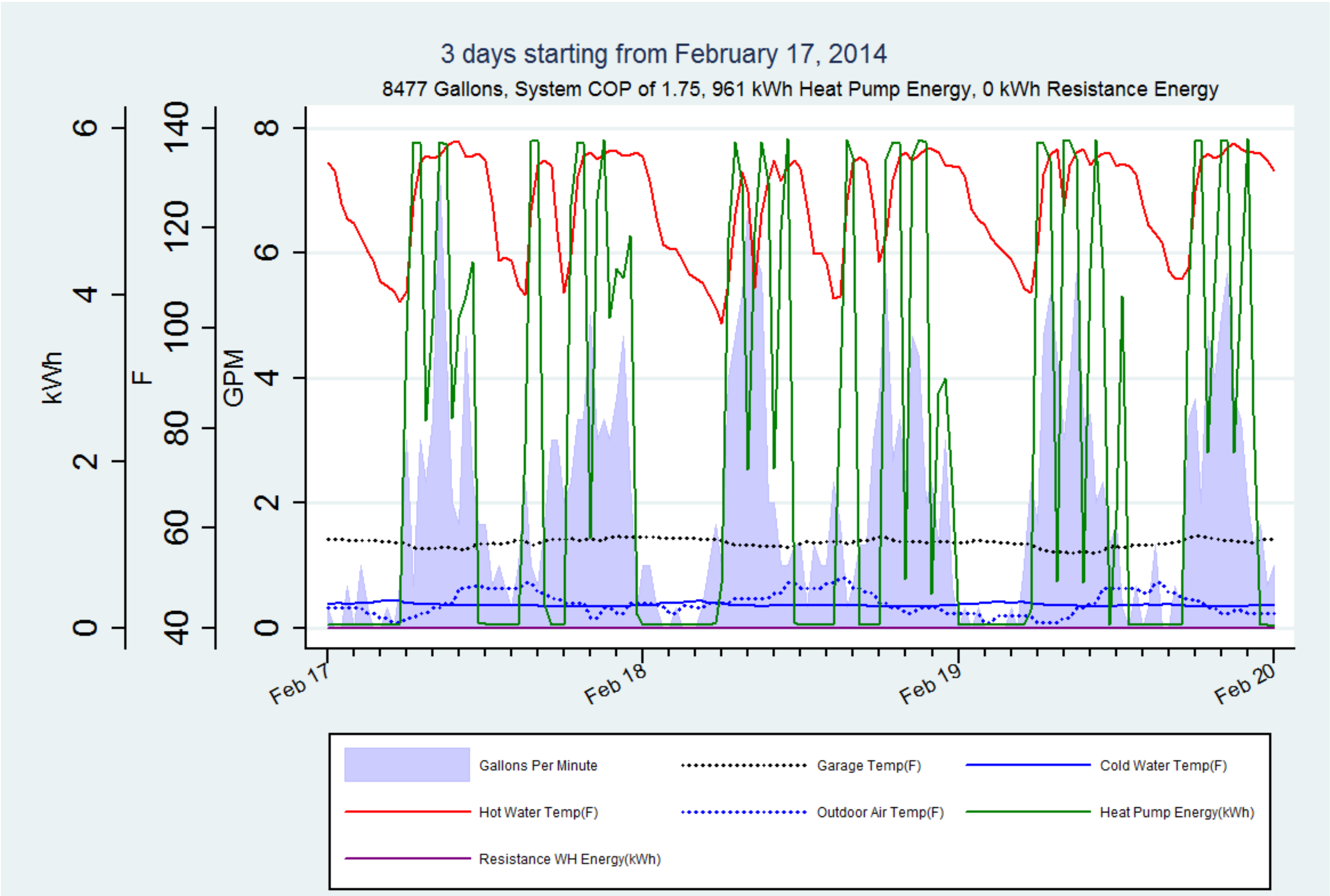

Figure 13: Sample of Data After Piping Changes

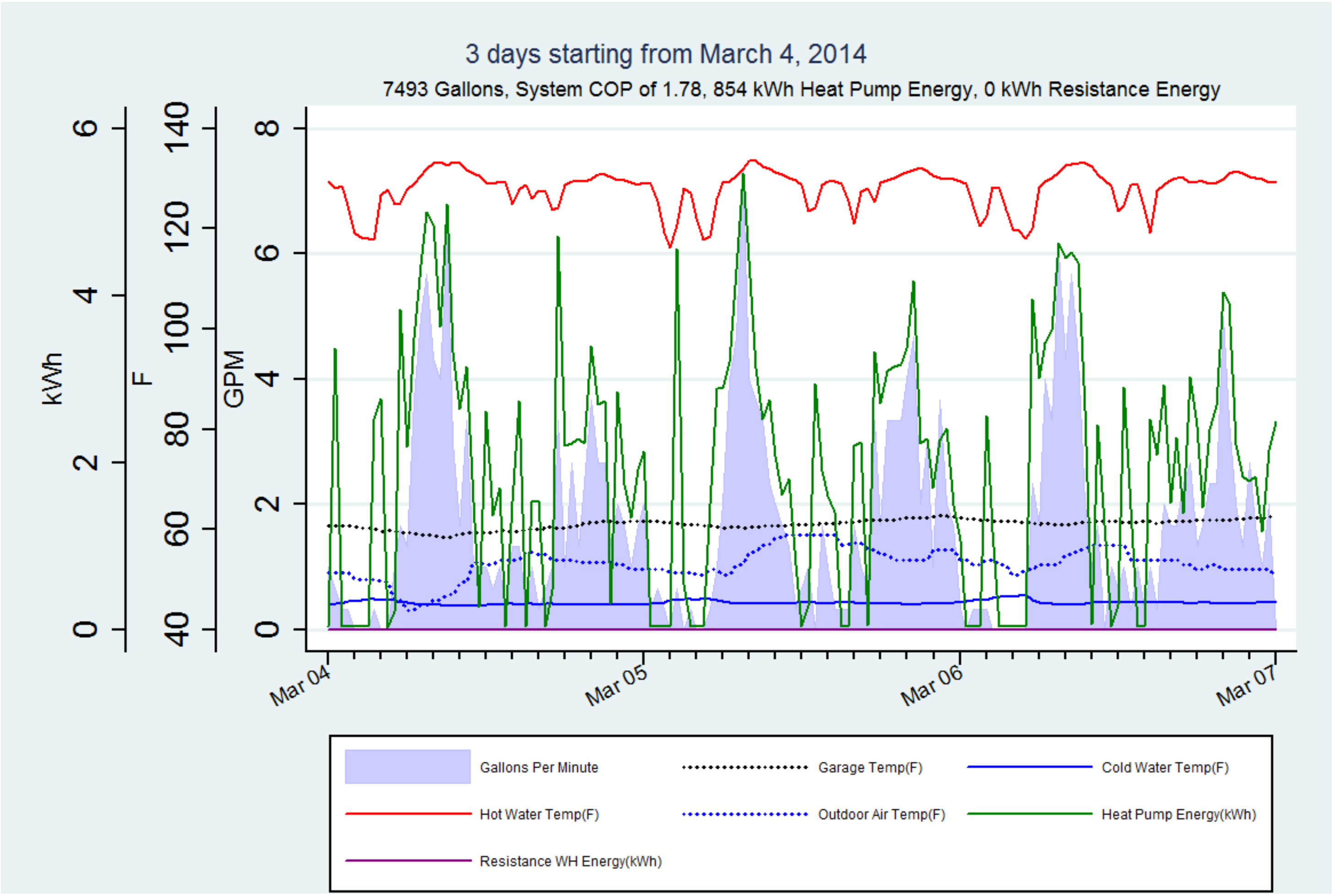

Figure 14: Sample of Data After Controls Problems Were Fixed

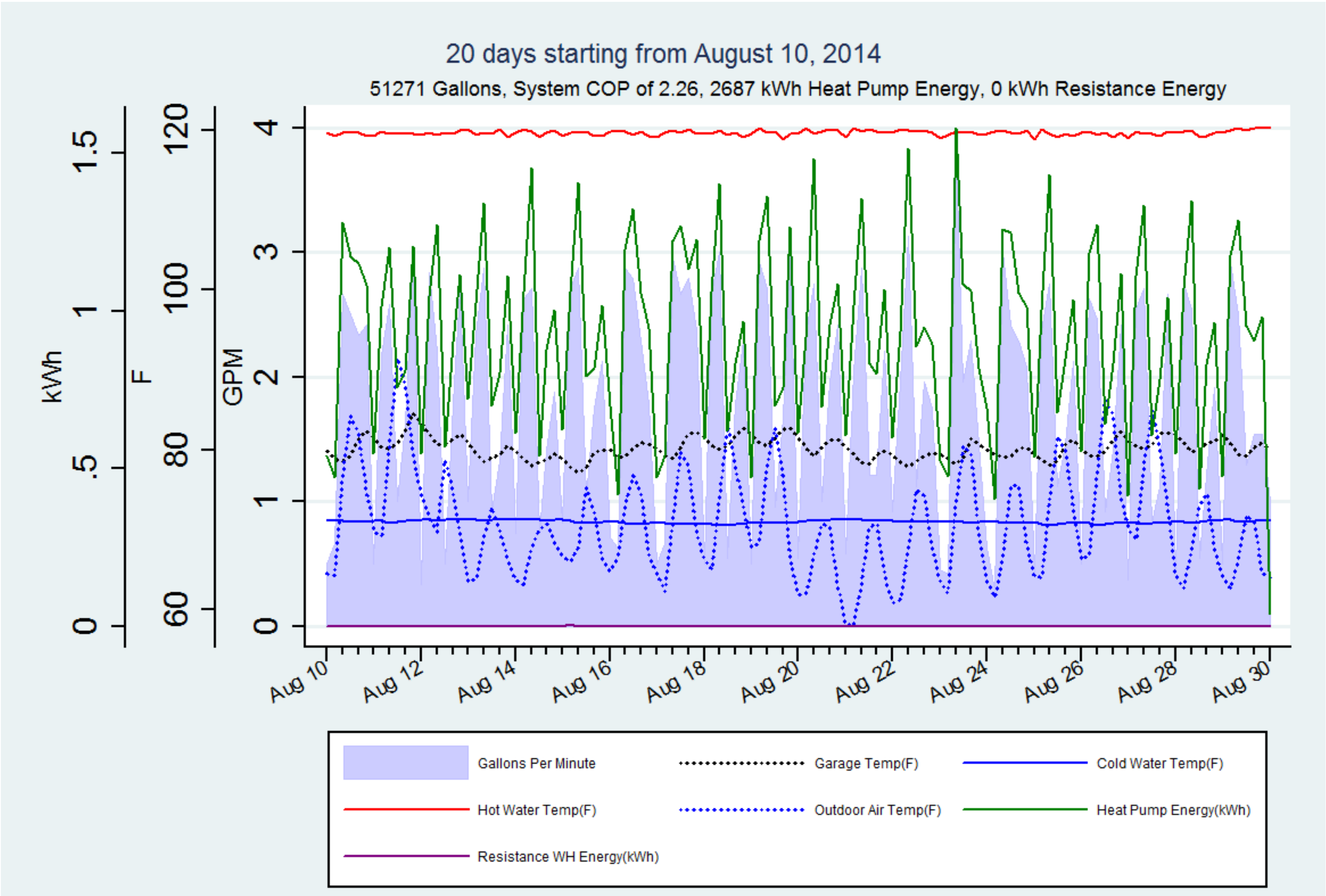

Figure 15: Sample of Data after Recirculation Pump and Tempering Valve Replaced

Sunset Electric Monitoring

The graphic below shows the performance of the Sunset system over a full year of operation as monitored by the M&V system. The monitoring allowed for the diagnosis of a number of anomalies and shows the impact of the various changes implemented.

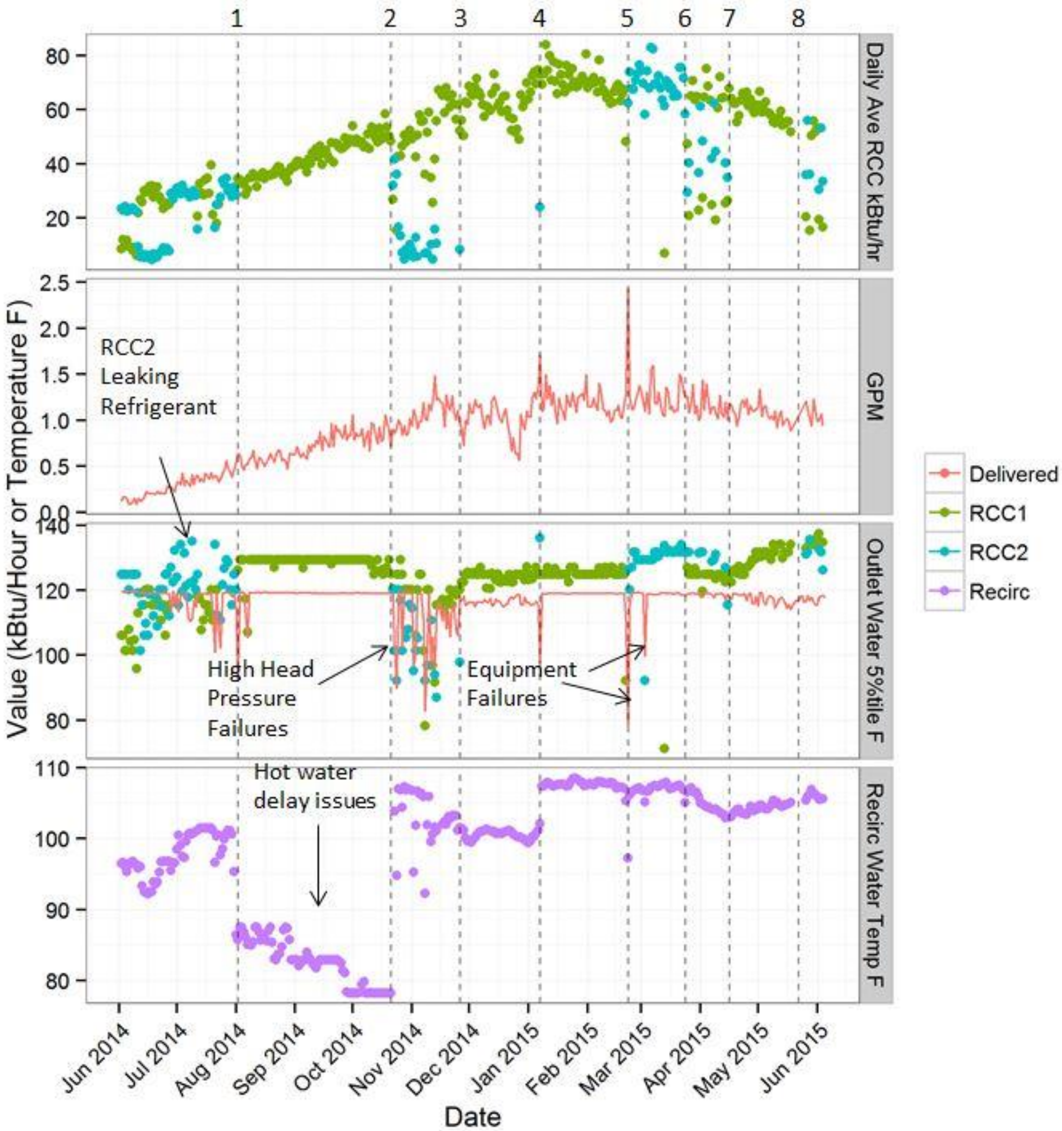

Figure 16: Sunset Electric Performance Over a Full Year

The numbered vertical bars identify specific events:

1. In the first period RCC2 was leaking refrigerant, so it was valved off (Event 1) and the hot water circulation loop was slowed down.

2. In the second period RCC1 was working well, but there was not enough circulation so it took a long time for residents to get hot water and there were many complaints. (Circulation flow was increased at Event 2).
3. In the third period the increased circulation flow led to high entering water temperatures to the heat pumps and many high head pressure failures. (Refrigerant was removed at Event 3).
4. In the fourth period operation stabilized but circulation temperatures were still too low to eliminate tenant complaints. (Circulation flow was increased as much as possible at Event 4).
5. In the next period operation was stable until compressor in RCC1 broke. (Event 5).
6. The sixth period shows RCC2 taking over water heating until RCC1 was fixed. (Event 6).
7. The 7th period shows both RCCs operating with a lead/lag controller until a sensor failure in RCC2. (Event 7).
8. The 8th period shows RCC1 taking over all operations until RCC2 was put back on-line. (Event 8).

Garage Air Temperatures

The parking garages are providing a significant temperature buffering effect for the RCC systems. The large high mass below grade surface area keeps the garage at a very constant temperature throughout the day and throughout the year. In addition to the earth buffering effects the garages gain additional heat from the lights, the cars, the sewer lines, connection to the heated space above, and heat loss from the RCC system itself. Figure 17 below shows the average daily garage temperatures compared to outdoor temperatures.

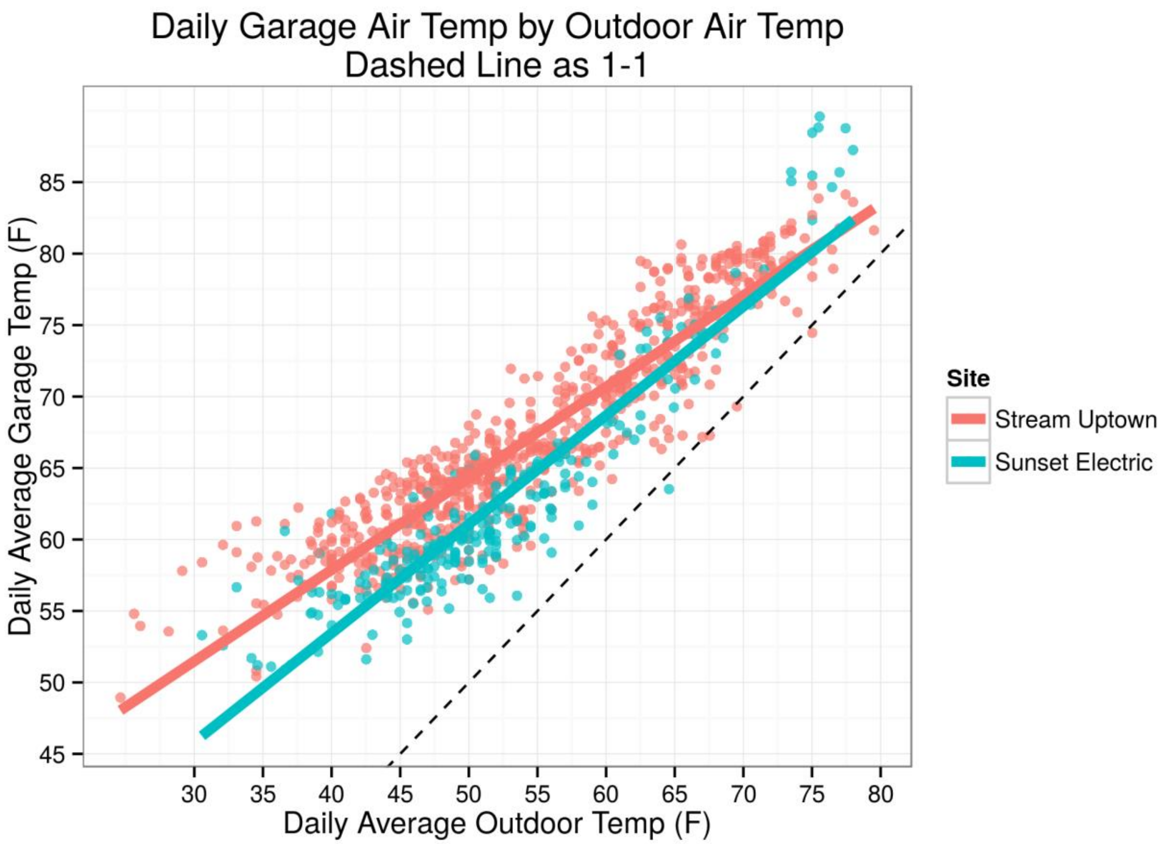

Figure 17: Garage Temperatures

Note that data landing on the dashed line would indicate that it is the same temperature in the garage as outside. Data to the left of the dashed line shows times when it is warmer in the garage than outdoors and data to the right are times when it is warmer outside. This clearly shows that the garages are providing overall warmer intake air basically every day of the year, with about an average of 10ºF higher average daily temperature. This improves the COP of the RCCs by about 0.5 compared to if they were operating outdoors (see Figure 20 below).

Figure 17 also shows that the Stream Uptown garage is on average about 3ºF warmer than the Sunset garage. It is not clear why this is the case. Note also that in the summer of 2015 we have seen the garage temperature spike in the afternoons at Sunset. This is due to the installation of a large AC unit used to cool a new restaurant in the ground floor of the building. This has contributed to afternoon temperatures as high as 90ºF in the Sunset garage. Other than these afternoon spikes due to air conditioning at the Sunset Electric building, the temperature in the garage is remarkably stable during the day; typically swinging only about 2ºF as shown in Figure 18 below.

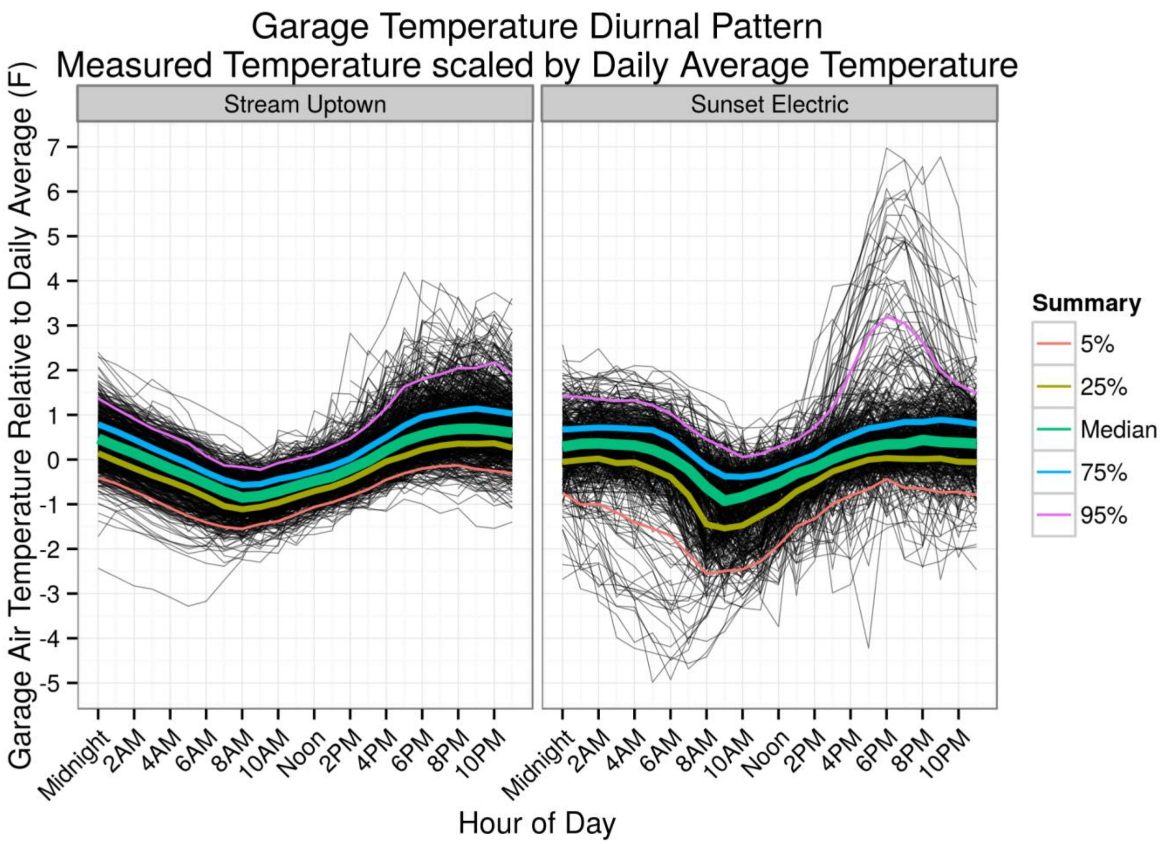

Figure 18: Garage Temperature Diurnal Pattern

Hot Water Usage

The Monitoring system enabled us to learn some interesting things regarding water usage in these new buildings. The amount of hot water used by the people in these two projects is surprisingly different. In the Stream project the occupants are using an average of about 19 gallons of hot water per person per day. At the Sunset project the occupants are using an average of only 13 gallons per person per day. The buildings have similar plumbing fixtures and are both primarily occupied by young urban professionals. However, they are in different neighborhoods with perhaps somewhat different demographic lifestyles. The Sunset building is in the heart of Capitol Hill which is a neighborhood of mostly young people with a very active street life. The Stream building has much less local amenities in the way of restaurants and activities.

Figure 19 below shows the daily profile of hot water usage.

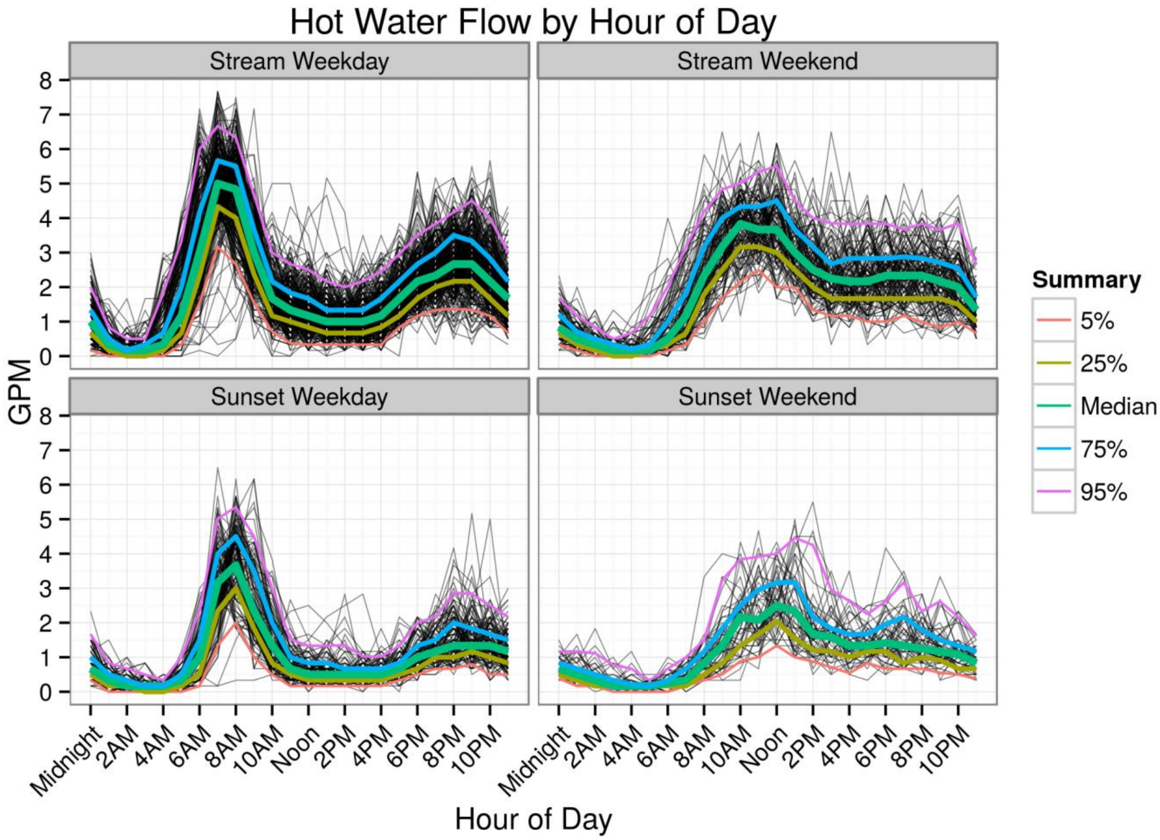

Figure 19: How Water Flow by Hour of Day

Note that there is a very different profile for weekday and weekend usage at both buildings with the weekend usage peaking later and continuing throughout the day with laundry and other activities. This compares to the weekday usage with a very large morning shower peak and somewhat less pronounced evening dinner peak, especially in the Sunset building. Interestingly the Sunset daily peak is a full hour later than the Stream daily peak.

System Performance

The performance data from the manufacturer of the RCCs is shown in Figure 20. It shows the strong dependence of the heating capacity and efficiency of the heat pumps to the source air temperature (wetbulb temperature of the parking garage) and the load temperature (leaving water temperature – LWT in the figure).

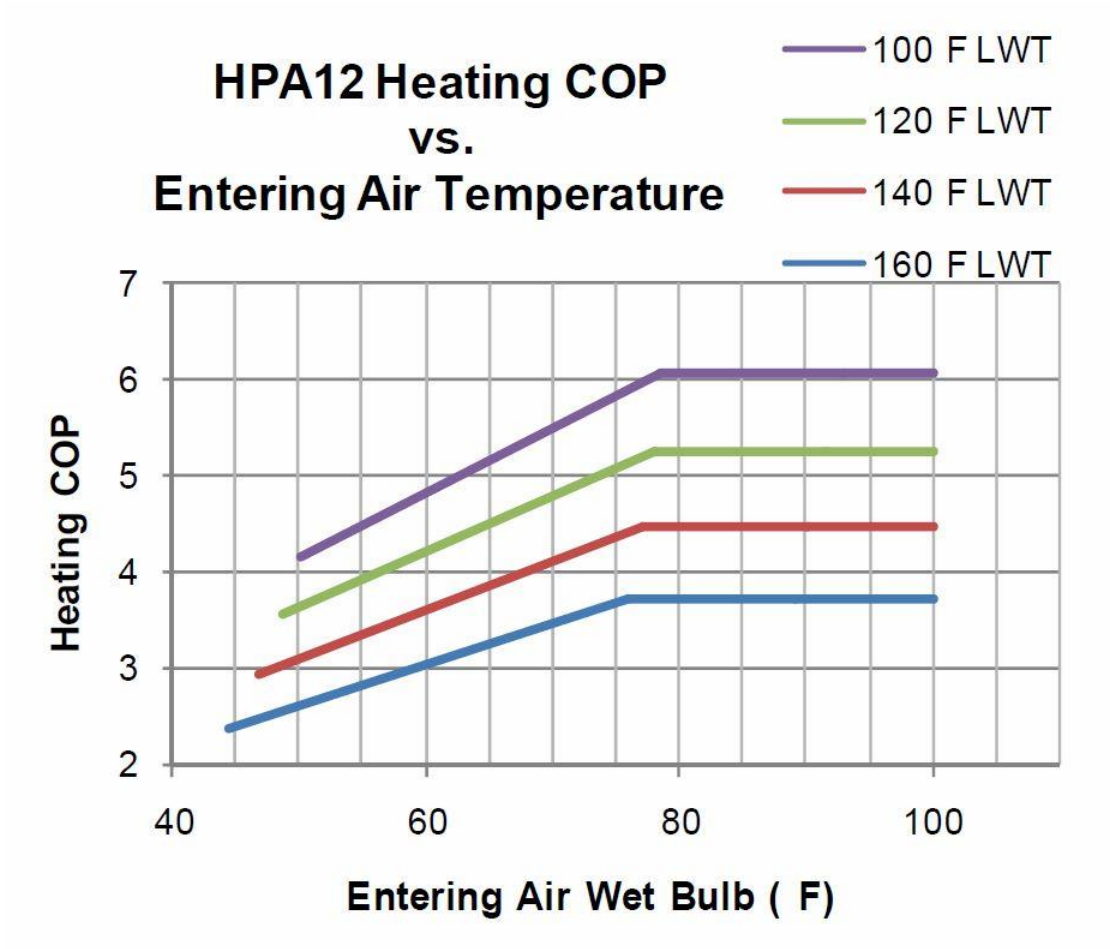

Figure 20: Colmac Manufacturer's performance data for RCCs

These graphs are based on an incoming water temperature of 70ºF. These performance curves would be appropriate if there were no hot water recirculation loop. However, since the recirculation loop brings warm water back to the system, the average temperature of the water entering the heat pumps is significantly higher (since it is being mixed with recirculated water). While we do not have performance data for the full range of incoming water temperatures we anticipate that the impact of the warmer water temperatures reduces the average COP of the heat pumps by approximately three-quarters of a COP point. [8] Using this adjustment to the manufacturer's published performance data we would expect the average annual COP at the Stream project to be in the range of 2.8-3.0.

[8] Based on lab testing of heat pump water heaters for BPA. A 40F increase in entering water temperature represents a 1 COP drop in efficiency. *Ben Larson et. al. Residential Heat Pump Water Heater Evaluation: Lab Testing and Energy Use Estimates. Nov. 9, 2011. Prepared for BPA E3T Initiative.*

This estimate matches reasonably well with the measurements of actual performance at Sunset Electric. The addition of "Btu-meters" at Sunset Electric allowed us to calculate actual equipment performance. Equipment performance varies seasonally with incoming water temperatures and garage air temperatures. Measured COP at Sunset ranges from a low of about 2.2 in the winter to a high of about 2.5 in the summer for a longterm average estimated to be about 2.4 year-round.

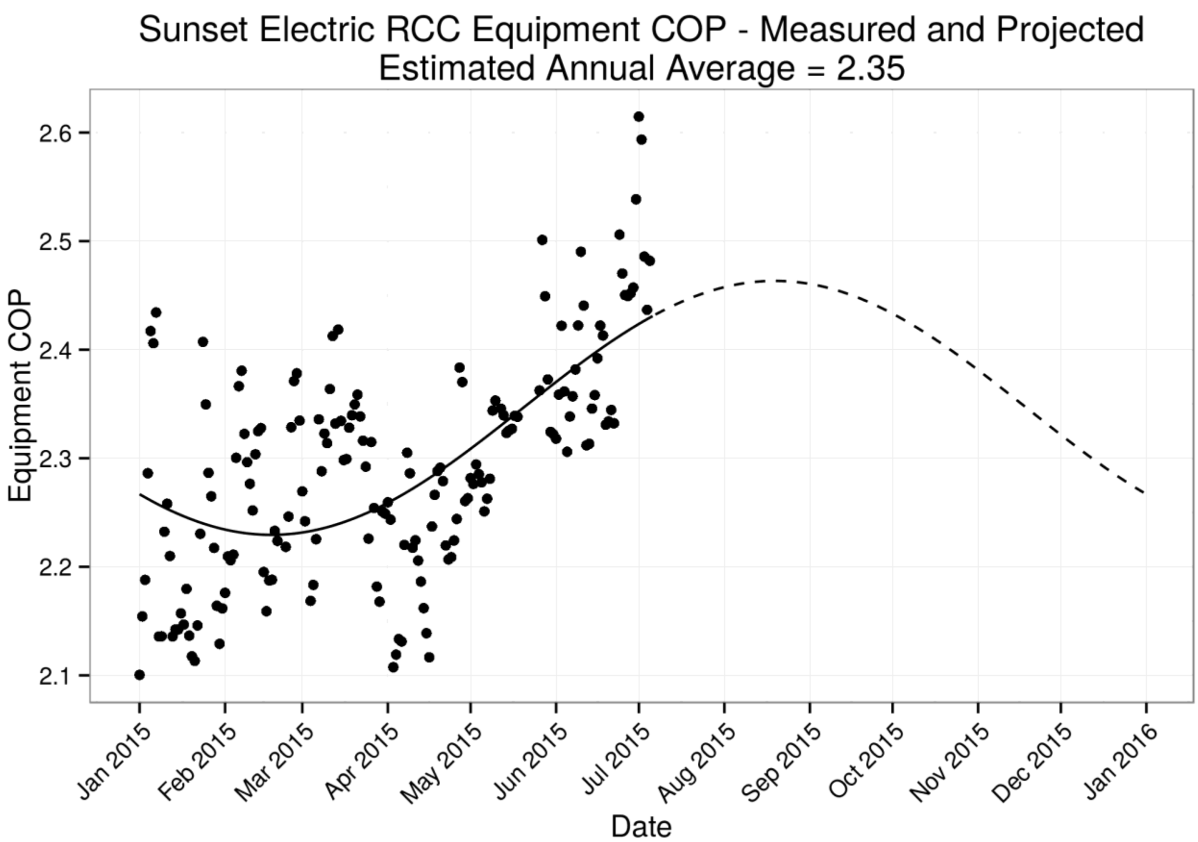

Figure 21: Sunset Electric RCC COP

A number of factors at the Sunset Electric Apartments combine to produce a lower average annual COP for Sunset than for the Stream Uptown project:

1. The Sunset RCCs were delivered with 5 HP fans compared to the standard 3 HP fans used at Stream.
2. The average garage air temperature at Sunset was consistently about 3ºF cooler than at Stream.[9]

[9] A restaurant was added to the Sunset building in 2015 with a large AC compressor located in the parking garage. Starting in June 2015 we have seen very high afternoon air temperatures in the Sunset garage due to the operation of that AC unit.

3. The incoming water temperature from the street is about 4ºF warmer at Sunset than Stream. Warmer entering water temperature leads to lower equipment COP.
4. The water usage at Sunset is significantly lower than at Stream. This is due to both fewer occupants (~110 vs. 140), and significantly less hot water used per person (~30%). This also raises the average temperature of the water entering the RCCs; lowering the COP.

The combined effect of the above factors reduces the average annual COP from about 2.8-3.0 at Stream to about 2.4 at Sunset. These performance numbers also compare well with the average annual performance of 2.6 predicted by the original feasibility study.

The M&V systems were able to determine the useful hot water consumed and the amount of electrical energy needed to provide that hot water. This gives an overall "system efficiency" for hot water delivery. However, we are not able to determine exactly where all of the heat is going. The heat produced by the water heating system goes to one of the following locations:

1. Useful heat into incoming cold city water; consumed as hot domestic water in the apartments (showers, laundry, etc…)
2. Heat loss from piping and storage tanks in the garage. This heat is lost, although some of it is recaptured as heat in the parking garage entering air to the heat pumps.
3. Heat lost in the recirculation loop inside the building. This heat is lost from the water heating system, although some of it ends up as useful heat in the winter offsetting space heating energy in the building.
4. Heat lost in the standing water in non-recirculating piping in the apartment units between the fixtures and the recirculation loop. Again, this energy is lost but some of it offsets space heating energy in the winter.

Note that some fraction of the heat loss from the water heating system inside the building offsets space heating that would otherwise have been supplied by the space heating system. This likely represents an overall reduction in energy use for the building since the space heating system is electric resistance with a COP of 1 and the water heating system is a heat pump with a COP of about 2.6. It is not clear how much this effect offsets the losses from the hot water distribution system. If 38% of the heat lost from the distribution loop ends up offsetting electric resistance space heat, then the losses are completely balanced by the increase in space heating efficiency. Therefore in a building heated with electric resistance space heating, the distribution losses from an RCC system are likely not a large net increase in annual energy use (the losses in the summer are made up for by heating efficiency gains in the winter). Note that this is not the case if the building is heated with ductless heat pumps. In the latter case, losses from an RCC system with a COP of 2.6 are offsetting space heating with a COP of 3 instead of electric heaters with a COP of 1.

The actual useful heat provided for domestic water heating is the mass of hot water consumed at the fixtures times the temperature difference between the incoming city water temperature and the hot water temperature delivered to the apartments.[10] We can then define an overall **System COP** as the useful heat delivered divided by the electrical energy used by the water heating system. This is a measure of the overall production, storage, and distribution efficiency since it counts only the heat that was actually consumed at the fixtures in the numerator[11]. The following table summarizes the data from the two projects:

Table 1: Summary of System Performance Information

Measure	Range	Stream	Sunset
Apartments		118	92
Occupants		140	110
Garage Temp ºF	Average	66	63
	High (99%)	81	83
	Low (1%)	53	50
Hot Water (Gal/Person/Day)	Average	19	13
	High (95%)	23	18
	Low (5%)	16	-
RCC COP	Average	2.8*	2.4
	High	-	2.5
	Low	-	2.2
Losses	kBtu / year	200,000	210,000
	Average %	30%*	44%
RCC Energy Use		262,000**	210,000

*Estimate based on manufacturer's data.

**Excluding periods of electric resistance operation.

Losses in the table above refer to the heat lost from the storage, distribution, and hot water circulation system. The losses at the Sunset project are a much higher fraction of the total energy used by the water heating system than they are at Stream. However, the actual losses are within 5% of each other. At sunset the loss from the loop is about 261 BtuH/apartment compared to about 193 BtuH/apartment. Note that this is about the same as the losses from a typical full sized electric water heater of about 205 Btu/hr. This

[10] $Q=mc_p(T_{out}-T_{in})$ where Q is useful heat provided in BTUs, m is lbs of water, c_p is heat capacity of water (1Btu/lbºF) and $(T_{out}-T_{in})$is the temperature rise imparted to the water.

[11] This is not exactly correct since we assume that the temperature of water used at the fixture is the same as the temperature delivered to the distribution system by the tempering valve. In reality it will have cooled slightly before use.

indicates that the distribution losses from these central water heating system are not significantly different from the losses from individual water heaters in the apartment units.

Interactive Effects and Comparisons to Typical Equipment

If we are comparing a central RCC system to a central electric boiler or central gas water heating system, we can use the equipment efficiency as the comparison since the distribution losses should be approximately the same regardless of the water heating plant used. In this case an RCC system will use approximately 36-42% of the water heating energy used by an electric boiler system, and 29-33% of the water heating energy used by a gas boiler with 80% combustion efficiency. This represents about a 15% reduction in the energy use of the entire building based on typical mid-rise multifamily construction in the Seattle area.[12]

However, since some of the distribution losses go to offset space heating energy, the overall effect on the total energy use of the building is somewhat more complicated. If we install an RCC system in an electrically heated building then the savings are increased by the amount of space heating offset that occurs. This interactive effect is rather hard to estimate. However, if we assume that 1/3 of the distribution losses go to offset electric space heating, then the distribution losses from the RCC system are nearly neutral in terms of total building energy use. In this case the RCC represents about an 18% reduction in the total energy use of the building compared to an electric resistance or gas boiler water heating system.

Conclusions

This project demonstrated the RCCs can yield significant energy savings for multifamily buildings in the Pacific Northwest climate. The pilot projects demonstrated an overall reduction in hot water energy use of between 55-70% and an overall reduction in the total building energy use of 15-18% for a typical mid-rise multifamily building in Seattle WA.

The pilot projects demonstrate that installation of this class of RCC equipment in below grade parking garages can yield significant performance benefits due to the thermal buffering effects of the garages, and the systems can run at relatively high efficiencies year-round without the need for supplemental heating.

Estimates from these pilots indicate that about 30-45% of the heat produced by the RCCs is lost through conduction out of the distribution and storage system. Reducing these losses is an important aspect of creating a high efficiency central domestic water heating system. This part of the design is typically controlled by the plumber. It is important that such systems have clear performance specifications to include insulation without thermal bridging on all parts of the distribution system. However, it is important to note that some of the losses from the piping offset space heating that would otherwise have to be produced by the space heating system. If the space heating system is electric resistance (the most common system in Seattle multifamily buildings), then the losses are offset by the higher efficiency of heat produced by the RCC system.

[12] Jonathan Heller, K. Geraghty, and S. Oram. *Multifamily Billing Analysis: New Mid-Rise Buildings in Seattle.* Ecotope. Dec. 2009. Prepared for City of Seattle Department of Planning & Development.

Entering water temperature has a large impact on the efficiency of heat pump water heaters. Efficiency drops dramatically as inlet water temperature increases. The hot water recirculation coming back to the storage system raises the water temperature supplied to the heat pumps with a consequent efficiency penalty. Managing this recirculated water is a critical design issue to solve in future RCC designs. There are various possible ways to reduce this impact. The most important is to reduce the heat loss of the distribution and recirculation piping by optimizing the piping design and insulating the piping. The recirculation loop could also be treated separately by a small heat pump so that the recirculation does not interact with the main storage system.

The specification of the equipment itself is important to the performance of the overall system. Sizing and efficiency of the fans and pumps associated with the system can have a large impact on the overall system performance.

While the measurement and verification (M&V) metering equipment installed was primarily conceived to evaluate the performance of the equipment, it also served the purpose of allowing us to diagnose and solve operational problems that were negatively impacting the performance. Without the M&V equipment it would not have been possible to figure out what was happening with the system and how to improve operations. Some level of M&V equipment for the purpose of troubleshooting should be included in all emerging technology installations.

Lessons Learned

- Aquastat location is important. Locate aquastat far enough away from incoming water to avoid triggering aquastat every time any water is used. Time delay built into RCC operation can help with this.
- Typical non-electric tempering valves do not function well with varying inlet water temperatures. Consider use of electronic tempering valves.
- Balancing the hot water circulation loop is critical to a properly functioning system. Too low of a flow rate leads to cool return water temperatures and complaints from the tenants about long waits for hot water. Too fast of a flow rate flushes through the storage tanks and can lead to too hot water being fed into the RCCs. Consider use of a separate heater dedicated to the circulation loop.
- Heat lost from the circulation loop and distribution piping can account for 30-45% of the heat produced by the RCC system. Pay close attention to the insulation of the circulation and distribution piping. Eliminate all areas of thermal bridging.
- In a building heated with electric resistance space heaters, the losses from the distribution and circulation piping are at least partially offset by reduction in electric resistance space heating systems.
- Selection of equipment is important for system efficiency. Pay attention to selection and proper sizing of fans and pumps. These auxiliary items can have a big impact on overall system COP. Use no more than 150 Watts/ton of heat pump capacity for auxiliary pumping and fans.
- Include robust measurement, verification, monitoring, and alarming functions with any emerging technology design to assist in diagnosing issues and improving future designs.

The primary conclusions and lessons learned from these pilots have been incorporated into an RCC Design Guidelines document produced for Seattle City Light and funded by the Bonneville Power Administration's Emerging Energy Efficient Technologies program. This guide has been incorporated here as Appendix A.

Appendix A: Reverse Cycle Chiller (RCC) Best Practices Design Guidelines.

Reverse Cycle Chiller (RCC) Best Practices Design Guidelines

Submitted to: Seattle City Light

Prepared by:

Jonathan Heller, PE

Shawn Oram, PE

December 2015

Executive Summary

This report provides best practices recommendations for design of heat pump water heating systems in multifamily buildings in Seattle using Reverse Cycle Chiller (RCC) technology. RCCs are commercial air-cooled chillers setup with reversing valves to function as heat pumps to create hot water as opposed to chilled water.

Recommendations in this design guide have been developed based on experience gathered during a pilot project of this technology funded by the Bonneville Power Administration's Emerging Energy Efficient Technologies (E3T) program. This project funded design assistance, commissioning, and Measurement and Verification (M&V) studies of two RCC installations in multifamily buildings in Seattle. Lessons learned from those projects have been incorporated here to propose a design approach that delivers high efficiency, reliability, redundancy, low cost, and does not require non-heat pump back-up equipment. Some of the key design features needed to ensure a high level of consistent performance include the following:

1. Install RCCs to pull supply air from a below grade parking garage to provide warm air year-round to the RCCs.
2. Set up RCCs to function in "single pass" mode; varying water flow through the heat exchanger to deliver a fixed outlet water temperature to the hot water storage tanks (120F minimum).
3. Provide temperature stratified hot water storage; most easily accomplished with multiple storage tanks in series.
4. Use latest ASHRAE sizing methodology outlined in the 2015 ASHRAE Handbook: HVAC Applications, Chapter 50, page 50.16 to size total storage and heat pump capacity.
5. Provide multiple stages of water heating equipment arranged in parallel and stage them in a lead/lag configuration. Provide controls to prevent short-cycling of compressors.
6. Provide full insulation on all distribution and recirculation piping to limit heat loss from the piping system. Eliminate thermal bridging at piping supports. Provide insulated water tank jackets for storage tanks.
7. Consider inclusion of a separate small heat pump water heater to maintain the temperature of the recirculation loop. Do not use electric resistance or gas fired equipment for hot water circulation reheating.
8. If back-up (gas or electric resistance) equipment is used, configure for emergency-only operations.
9. Optimize the performance of all of the components of the RCC system such as compressors, heat exchangers, pumps, and fans. Select a combination of fans and pumps using no more than 150 Watts per nominal ton of RCC capacity.
10. Include basic alarm notifications and measurement and verification equipment to allow for monitoring and troubleshooting of system performance over time.

In apartment buildings heated with electric resistance space heating a typical RCC installation following these general guidelines can be expected to reduce the required energy use of the hot water system by approximately a factor of 2.6.

Introduction

In 2009 Ecotope completed a feasibility study for the Bonneville Power Administration (BPA) Emerging Energy Efficient Technology (E3T) program.[1] The study examined the use of Reverse Cycle Chillers (RCC) to produce domestic hot water for multifamily buildings in the Pacific Northwest. An RCC is essentially commercial chiller technology set up to operate in reverse as a heat pump water heater and equipped with a double-walled copper heat exchanger so that it can process potable water directly. The RCCs used in the study contain R-134a refrigerant which does not function well at supply air temperatures below about 40F. The innovation in this study was to take advantage of the thermal buffering effects of below grade parking garages to allow the use of R-134a heat pump technology year-round at relatively high efficiency for the production of domestic hot water in the Pacific Northwest climate.

Following the feasibility study two multifamily building projects in Seattle were recruited for pilot projects. In addition to support for the pre-design work carried out in the feasibility study, BPA provided funding for system commissioning, and a Measurement and Verification (M&V) study. Seattle City Light provided energy conservation incentive money for both projects. The M&V data allowed for a number of issues to be identified and corrected in the pilot projects and led to changes to improve the design and overall performance. Lessons learned from the pilot projects has contributed to the recommendations included in this Design Guide.

Figure 1: Stream Uptown Apartments – The first RCC Pilot project to be completed in Seattle

Based on the performance of the first two RCC pilot projects it is clear that RCCs can be used effectively in the Seattle climate to produce domestic hot water in multifamily buildings at a COP of around 2.6

[1] Reverse Cycle Chillers for Multifamily Buildings in the Pacific Northwest: Phase I Final Report. Jonathan Heller and Carmen Cejudo, Ecotope Inc. September 2009. Produced for the Bonneville Power Administration.

without the need for back-up electric resistance or gas heat. However, there are a large number of potential design pitfalls that will reduce reliability and/or energy efficiency of an RCC system. The intent of this Design Guide is to present some of the critical issues to be addressed by RCC designs in the Seattle climate to ensure a highly efficient and effective water heating system. It also presents recommendations for design features that should be included in all RCC designs to be provided with Seattle City Light energy conservation rebate money and expected savings from these systems.

Available Air-to-Water Heat Pump Equipment

Air-to-water heat pump technology is available in a wide range of configurations; some of which are appropriate for heating domestic hot water in multifamily buildings in the Pacific Northwest. The various classes of available Air to Water Heat Pumps are shown in the photos below and described in Table 1.

Integrated Units

Small CO2

Split System R410a

Multi-Pass RCC

Single Pass RCC (CO2)

Single Pass RCC 134a

Figure 2: Range of Available Heat Pump Water Heating Equipment

Table 1: Classification of Various Commercially Available Air-to-Water Heat Pump Equipment

Make/Model	Description	Refrigerant	Equipment Capacity	Single or Multi-Pass	COP Range
GE, Rheem, AO Smith, Steibel Eltron, etc.	Integrated Units (heat pump and tank)	R-134a	4,500-8,700 Btu/hr + 4500 W Electric	Multi	1.6 (Recirc reheat) 2.4 (city cold water)
Notes: This equipment was designed for the single family market. Banking a few of these to serve as a central water heating system for a small multi-family (MF) building is feasible. These are also useful for dedicated recirculation water reheating. These units work in heat pump mode down to ~37F entering air so ideally these are located in an area with some amount of earth buffering or waste heat.					
Sanden Eco (CO2)	Packaged Units with storage tanks	R-744 (CO2)	15,000 Btu/hr	Single	3.2 (city cold water)
Notes: Useful for small to medium size MF buildings as a single pass primary heat plant, the peak hot water flows limit design options as each tank has only a 3/4" connection, piping these in parallel is a solution to larger incoming water flows, requires additional storage downstream. Outputs 149 F water at low flow rate. Not suitable for any other use beside primary cold water heating in a single pass (need separate system for reheating of circulation loop).					
Daikin Altherma	Split or Monoblok No Tank	R-410a	24,000-54,000 Btu/hr + 6kW Electric	Multi	2.0-3.0
Notes: Useful for small to medium size MF buildings. Low temp, multi-pass. Not rated for potable water - requires heat exchanger for double wall potable protection. Works as heat pump down to -5F entering air so it can be installed outdoors. These units may require back-up gas or electric trim tank for final heating.					
Heat Harvester, AO Smith, MultiStack, Aermec, Colmac	Multi pass commercial units	R-410a	100,000-420,000 Btu/hr + 6kW Electric	Multi	2.0-2.5
Notes: Potentially useful for medium to large size MF buildings. Low temp, multi pass. Not rated for potable water - requires heat exchanger for double wall potable protection. Works as heat pump down to -5F entering air so it can be installed outdoors. These units may require back-up gas or electric trim tank for final heating.					
Colmac, Single Pass	Single Pass Commercial Units	R-134a	48,000-180,000 Btu/hr	Single	2.8-3.2 (city cold) 1.8-2.0 (hot water circulation)
Notes: Single Pass, output 130-160F, can take up to 120F entering water. Works down to 40F entering air – ideal for below grade parking garage.					
Mayekawa	Large single pass Commercial Units. (0 GWP)	R-744 (CO2)	200,000 Btu/hr	Single	3.0-4.0 (city cold) 1.8-2.0 (hot water circulation)
Notes: Single Pass, output 149F or 194F water, needs high lift (100 degrees above entering water temperature). Peak entering water 95F. Works down to -5F entering air, not recommended for hot water circulation – include separate unit for reheating circulation loop.					

The BPA pilot project was focused on larger commercial fixed-capacity chiller technology with R134a refrigerant setup in a single pass arrangement. This is equipment is well-suited to the problem of multifamily water heating as it is capable of producing water up to about 160F from relatively cold air. The Single Pass setup is ideal for primary water heating as it does not require the use of a gas or electric resistance back-up “finishing” tank. Due to poorer low temperature performance of this equipment it is most appropriate where it can be buffered from ambient winter conditions such as locating it in below grade parking garages. This type of equipment and installation will be the primary focus of this design guide.

Figure 3: Colmac Industries RCC Equipment

Recommended Measures

The following is a list of measures recommended for inclusion in an RCC design in the Pacific Northwest climate based on 134a equipment installed in below grade parking garages.

1. Locate RCCs in below grade parking garage. Vent air to the outside.

There is a wide range of performance characteristics in RCC technology. The performance varies based on the equipment manufacturer and model as well as based on the energy content of the source air and the temperature of the inlet and outlet water. Figure 4 shows the theoretical heating performance of a typical 134a RCC compared to source air wetbulb temperature.

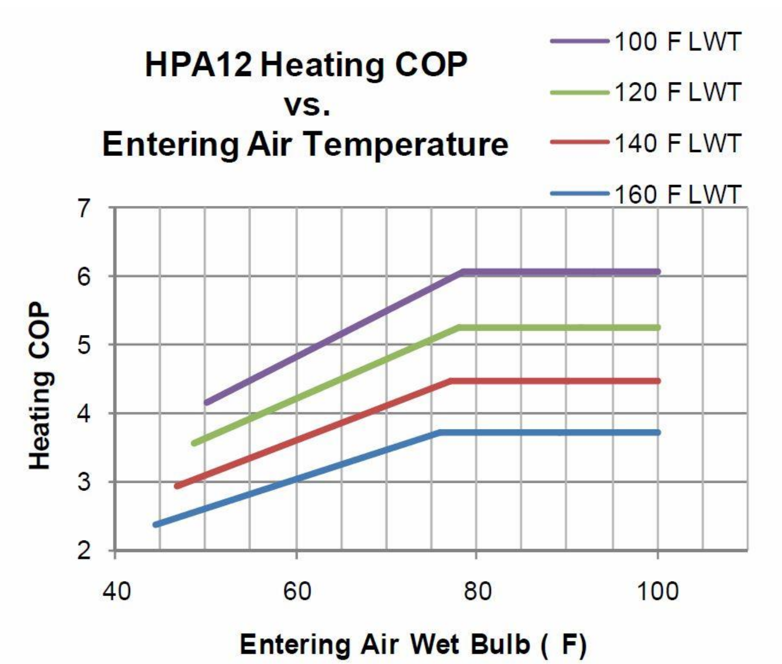

Figure 4: Manufacturer’s performance curves for RCC (70F entering water temp)

The warmer the source air, the higher the efficiency of the RCC. Note also that no data is shown below about 40-50F. This is due to the fact that the 134a refrigerant type RCCs will likely spend a lot of time in defrost mode when temperatures drop that low. This indicates that outdoor air is not a good source for this type of equipment in the Pacific Northwest for a year-round load such as domestic hot water since during much of the winter we experience temperatures below about 40-50F.

However, data from the pilot projects indicates that below grade parking garages in this region will remain above 50F year-round. The garages in the pilot projects were close to “worst case scenarios” for this type of application since they are both relatively small, not fully below grade, one includes a large number of space heating heat pumps which are extracting heat from the space, and the other is located below a large exterior courtyard rather than a heated building. Even in these locations the lowest average daily temperature did not drop below about 50F at any time during the year.

The figure below shows the average daily temperatures in the parking garages of the two pilot projects compared to the dotted line showing outdoor temperature. Note that it is warmer in the parking garage than outside for all but a small number of very hot summer days. This indicates that there is a significant COP benefit to locating the RCCs in the garages (~0.5 COP points). Note that the exhaust air from the RCC should be vented to the outside of the garage so as not to further cool the garage. This can serve the dual purpose of ventilating the parking garage.

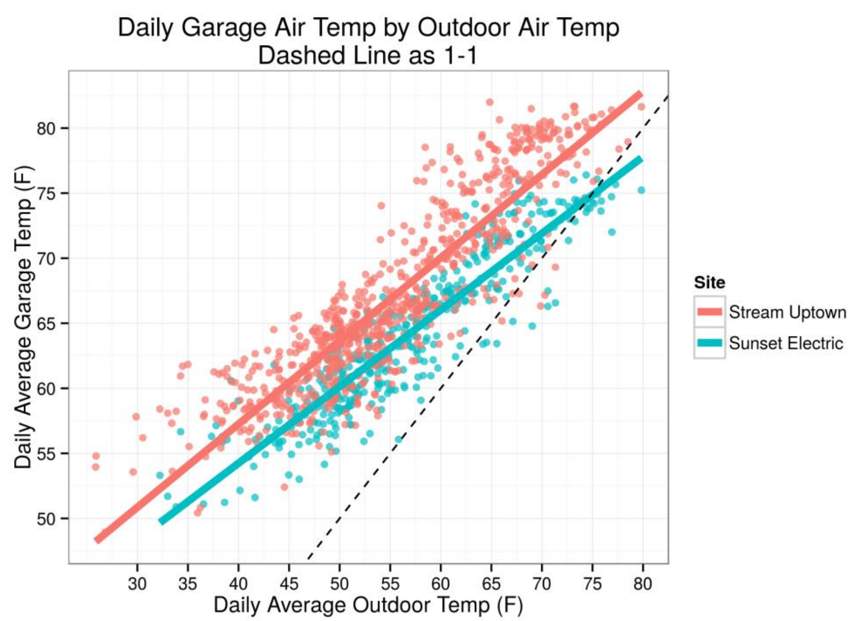

Figure 5: Measured Temperature in Below Grade Parking Garages in 2 RCC Pilot Projects

The next figure shows that the temperature in the garage is remarkably constant throughout the day. It tends to vary only 2-3F from a low point in the morning to a high point in the evening.

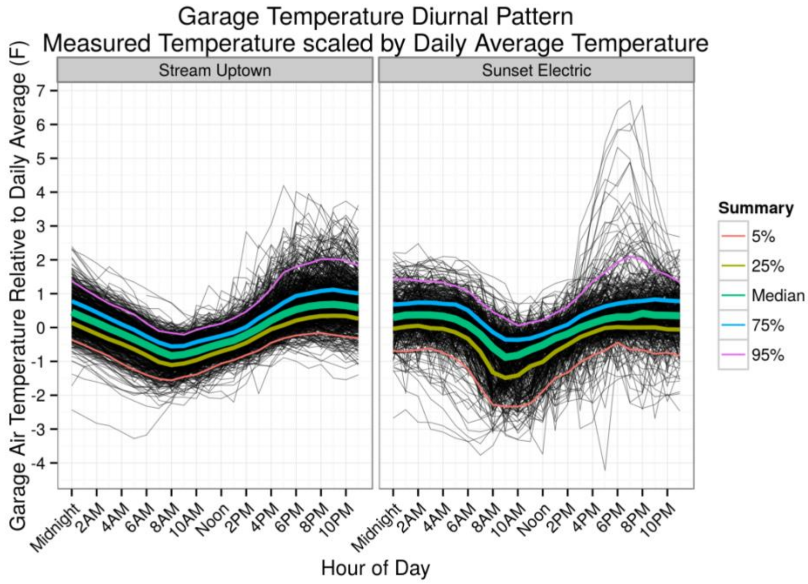

Figure 6: Daily Swing in Temperature in Below Grade Parking Garages in 2 RCC Pilot Projects

2. Single Pass

The design should be based around a "Single Pass" water pumping strategy as opposed to the typical "Multi Pass" strategy employed in most hydronic heating applications. This means that the flow of potable water through the RCC is regulated by a control valve or variable speed pump to maintain a target output temperature of 120-140F. This results in a variable flow rate and variable temperature rise across the heat pump as opposed to the typical fixed flow rate and fixed 10-20F temperature rise on the water. The heat pump can therefore output water hot enough for direct delivery to the building with incoming water temperatures to the heat pump ranging from 40-110F. The advantage of the Single Pass arrangement is that a usable water temperature is always delivered to the top of the storage reservoir. If a Multi Pass logic is used it is likely that another non-heat pump system such as electric resistance or gas water heater will have to be used in a "finishing tank" configuration to ensure that hot enough water is always available to the building. Not all RCC manufacturers offer a Single Pass configuration option.

3. Multiple Storage Tanks

The design should be based around the use of multiple storage tanks plumbed in series. The series plumbing arrangement enables a high degree of temperature stratification throughout the system with the hottest water at the end of the storage system from where water is sent to the apartments. It also allows the use of smaller cheaper tanks that are easier to install. Tanks should be sized to provide approximately half of the daily hot water demand (see sizing discussion below).

Figure 7: Domestic Hot Water Storage Tanks in Parking Garage

4. Hot Water Storage and Heat Pump Sizing Calculations

When sizing storage volume and water heater output capacity for a domestic water heating system there is a trade-off between storage volume and heat pump capacity. With minimal storage volume the heaters must be sized to handle the peak expected instantaneous demand (e.g. on-demand water heaters). With high enough storage volume (over half of the daily demand) the heat output capacity could be as low as the average hourly demand. Somewhere between these extremes is the optimal combination of storage and capacity.

ASHRAE provides methodologies for sizing multifamily hot water systems based on the number of apartments which enables a trade-off of storage volume and heat output capacity. The older simplified methodology that is commonly used was developed at a time with much higher average fixture and appliance flow rates, higher average apartment occupancy, and potentially very different lifestyles compared to the current typical apartment tenant in Seattle. The systems for the pilot projects were sized based on this methodology and in practice are oversized by approximately a factor of 2. In addition to higher equipment cost and more space required, this leads to short cycle times on the heat pumps, which is hard on compressor equipment.

The 2015 ASHRAE Handbook: HVAC Applications provides an updated sizing methodology that is much more appropriate for modern multifamily systems. The methodology is detailed on pages 50.14-50.16 and provides *Low, Medium, and High* use curves for different demographic groups. The M&V data collected at the two pilot projects indicates that these apartments are using an average of 13-19 gallons of 120F water per person per day. Peak usage data shows that they are very close to the *Low* usage curves from the ASHRAE data.[2] Table 1 below shows the *Low* and *Medium* usage data from Chapter 50 of the 2015 ASHRAE Application Handbook referenced above. We recommend sizing calculations target sizing based on the *Low* no greater than the *Medium* flow guidelines for new Seattle buildings.

Table 2: Peak Gallons of Hot Water per Person at Various Time Intervals for Use Sizing RCC Systems per Methodology in 2015 ASHRAE Applications Handbook, Chapter 50

	Peak Minutes						Maximum	Average
Guideline	5	15	30	60	120	180	Daily	Daily
Low	0.4	1	1.7	2.8	4.5	6.1	20	14
Medium	0.7	1.7	2.9	4.8	8	11	49	30

Note that data from the Seattle pilot projects also indicates that standard design assumptions for sizing plumbing and hot water systems appear to be very conservative for modern apartments in Seattle. The highest average flowrate of hot water over the course of a year with a 10-minute data logging interval was about 10GPM at a building with 92 apartment units. This is an order of magnitude less than the peak hot water flow rate assumed by the calculation methodology of Appendix A of the 2012 Uniform Plumbing Code. The peak flow assumed by the plumbing code for the purpose of sizing the plumbing is over 200GPM of hot water. More realistic assumptions about hot water demand could potentially

[2] Both pilot projects included water conserving low flow plumbing fixtures.

significantly reduce the capital cost of apartment plumbing systems, but any changes to the plumbing sizes would have to be negotiated with the Authority Having Jurisdiction over the plumbing systems.

5. Multiple smaller heat pump stages

The expected lifespan of compressors such as those used in RCC equipment are typically more closely tied to number and frequency of start/stop cycles than they are to years of operation. Therefore to extend the useful life of a heat pump system it is best to limit the number of cycles per day. One way to accomplish this is to provide multiple smaller pieces of equipment that can be staged in with increasing load as opposed to one larger unit that will meet the load more quickly and cycle more frequently. This also provides a mechanism for providing for some redundancy in equipment. For example see the schematic in Figure 9. In the case of a 20-ton load during the peak period of water consumption, the system could be provided with two 10-ton heat pumps and an emergency back-up electric boiler. These can be staged in as needed with a single heat pump unit running most of the time and a second heat pump brought in only to meet peak loads. The back-up is then available when one of the first units is down for maintenance.

Another methodology to prevent short cycling is to implement a time lag between a call for heating and the initiation of the heat pump. A 30-minute time delay allows for more cold water to enter the system before starting the heat pump, thus providing for a longer run-time.

6. Manage hot water circulation loop

Well-functioning hot water circulation loops are an essential component of a central hot water heating system in a multifamily building. Hot water must be maintained at all times in the primary hot water supply pipe so occupants can get hot water at their fixtures within a reasonable time lag after turning on the water. Inadequate circulation systems lead to high water usage and high levels of occupant complaints. However, high flows of relatively warm water (105-115F) returning to the storage system can have negative effects on a heat pump water heating system. Heat pump efficiency is directly tied to incoming water temperature. Heating COP for the heat pump decreases with warmer incoming water temperatures.

Furthermore, if the temperature of the water entering the heat pump is too high the heat pump will not be able to reject all of the heat produced and the refrigerant head pressure will rise and cause the unit to fail on a high pressure alarm. The design of the storage and circulation must be managed to avoid high temperature water from entering the heat pumps directly.

One recommended effective method for reducing these problems is to provide a separate dedicated heat pump to maintain the circulation loop directly. This eliminates the interaction of the circulation loop with the primary water storage; ensuring that the primary heat pump system will always operate at peak efficiency with lower incoming water temperatures. The heat pumps treating the circulation loop can be optimized for the constant load and higher water temperatures associated with the circulation loop. See Figure 10 below.

7. Limit Distribution and Circulation Losses

A very large amount of heat is lost in the storage, distribution, and circulation of hot water from a central water heating system. With low water usage associated with low flow fixtures and less water-intensive lifestyles these distribution losses can account for a very high fraction of the total water heat energy. In the RCC pilot projects the distribution losses were 30% of the total heat energy created by the RCCs at one site and 45% at the second site. This amounts to approximately 55-75 Watts of continuous heat loss per apartment. This compares very closely to an average heat loss of about 60 Watts for a typical electric water heater tank.

An important conservation measure is to reduce these losses and increase heat pump water heater efficiency by paying close attention to the insulation of the water distribution and circulation piping. Every portion of pipe with circulating water must be insulated. The insulation should be continuous through the supporting clamps with technology similar to that shown in Figure 8. Current code requires R-4 or 1" insulation on hot water piping.[3]

Figure 8: Recommended Configuration for Full Pipe Insulation

Note that some fraction of the distribution losses heat up the building and offset heating that would otherwise have been accomplished by the building heating systems. Depending on the space heating system and distribution of heat loss, this may negate the importance of these losses. When the building is heated with electric resistance heaters the losses from the distribution system during the wintertime likely *decrease* the overall energy use of the building since the heat in the loop was created at a COP of about 2.6 and the heating offset would have been created by an electric resistance heater with a COP of 1. With this accounting of total building energy, if 38% of the heat lost from the distribution loop goes to offset electric resistance space heating equipment the overall energy impact to the building of the distribution losses is zero.

8. Configure Back-up Heat as Emergency Only

A back-up heat source may be provided for additional redundancy in case of compressor or other equipment failures. However, care must be taken in the controls set-up to guarantee that the back-up heating source does not operate unless there is a failure in the heat pump system. Improperly set-up back-up heating systems can lead to continuous energy usage which will draw down the overall water heating system efficiency. Ideally the controls set-up for the back-up are designed as a fool-proof manual switch-over to avoid inadvertent controls changes that could lead to the back-up system taking over the water heating without the building operator's understanding.

[3] Unfortunately plumbing insulation is currently a portion of code that does not receive adequate enforcement. Insulation is not reviewed by the plumbing inspector, nor is it reviewed during inspection of the envelope insulation.

9. Optimize Performance of RCC Components

Not all RCCs are created equal. The performance of RCC equipment varies based on manufacturer and varies within a manufacturer across the range of their equipment offerings. Below is a table listing the rated performance of various sizes of the same series of equipment from a single manufacturer.

Table 3: Sample of RCC Equipment Performance Data

Model	Heating Capacity (BTUH)	Cooling Capacity (BTUH)	Heating COP	Cooling COP
HPA4	66,141	52,573	4.87	3.87
HPA7 (Axial)	110,681	86,049	4.49	3.49
HPA7 (Centrifugal)	110,681	80,959	3.72	2.72
HPA9 (Axial)	130,056	100,943	4.47	3.47
HPA9 (Centrifugal)	130,056	95,853	3.8	2.8
HPA11 (Axial)	169,439	133,333	4.69	3.69
HPA11 (Centrifugal)	169,439	128,243	4.11	3.11
HPA12 (Axial)	207,107	164,806	4.9	3.9
HPA12 (Centrifugal)	207,107	159,716	4.37	3.37
HPA30 (Axial)	468,030	347,353	3.88	2.88
HPA30 (Centrifugal)	468,030	339,718	3.65	2.65

The heating COP varies by 33% across this range of equipment sizes. Note that, these COP ratings do not take into account the energy use of all potential variations of the peripheral uses of pumps and fans. The sizing and efficiency of these items is also critical to the overall performance of the equipment. The fans and pumps should be selected for energy efficiency and should be sized only as large as necessary or should include variable speed drives (VSD) if possible. Total energy for the fans and pumps associated with the RCC system should add up to no more than about 150 Watts per nominal ton of capacity. Also note that the manufacturer’s efficiency numbers are typically published for optimal water and air temperature conditions.

10. Monitoring, Alarms, M&V

A certain amount of measurement, monitoring, and alarm capability is essential with this type of system to ensure proper operation. With any emerging technology it takes time for the designers, contractors, maintenance providers, building operators, and owners to fully understand that technology; what is required to set it up properly and keep it functioning. Performance data is critical to understand what is actually happening with any such system. At a minimum the system should send automatic alarms to maintenance personnel when there is a failure so that repairs can be completed as soon as possible. Total energy use of the system must also be available to allow for tenant billing of water heat energy. Tracking of this energy use periodically will allow for analysis of ongoing system performance. Increasing energy use could be associated with refrigerant leakage or equipment failures. The ability to record temperatures at the outgoing water line, the circulation system return, and throughout the storage system is important to understanding the severity and potential source of occupant water temperature complaints.

Sample Schematic Configuration

Recommended example system schematics for an RCC system are shown below. Key features that incorporate the recommendations from above include:

- The storage is arranged in multiple tanks in series to maintain maximum temperature stratification.
- Multiple smaller heat pumps are arranged in parallel so that they can be staged in as needed and controlled for longer run times.
- Electric back-up heat is provided as a separate stage that can be brought on only in the case of emergency if the RCCs cannot satisfy the load.
- The heat pumps draw cold water from the first storage tank and deliver hot water to the top of the final tank in a "single pass" arrangement so that hot water is always available.
- Temperature sensors in each storage tank allow for optimization of controls and staging and diagnosis of any potential problems.
- Recommended sequence is to start first stage heat pump when temperature in the second storage tank drops below set point and to run until temperature in the first tank is up to setpoint. Control second stage heat pump on when temperature in third tank drops below setpoint and run until temperature in second tank reaches setpoint, and so on.

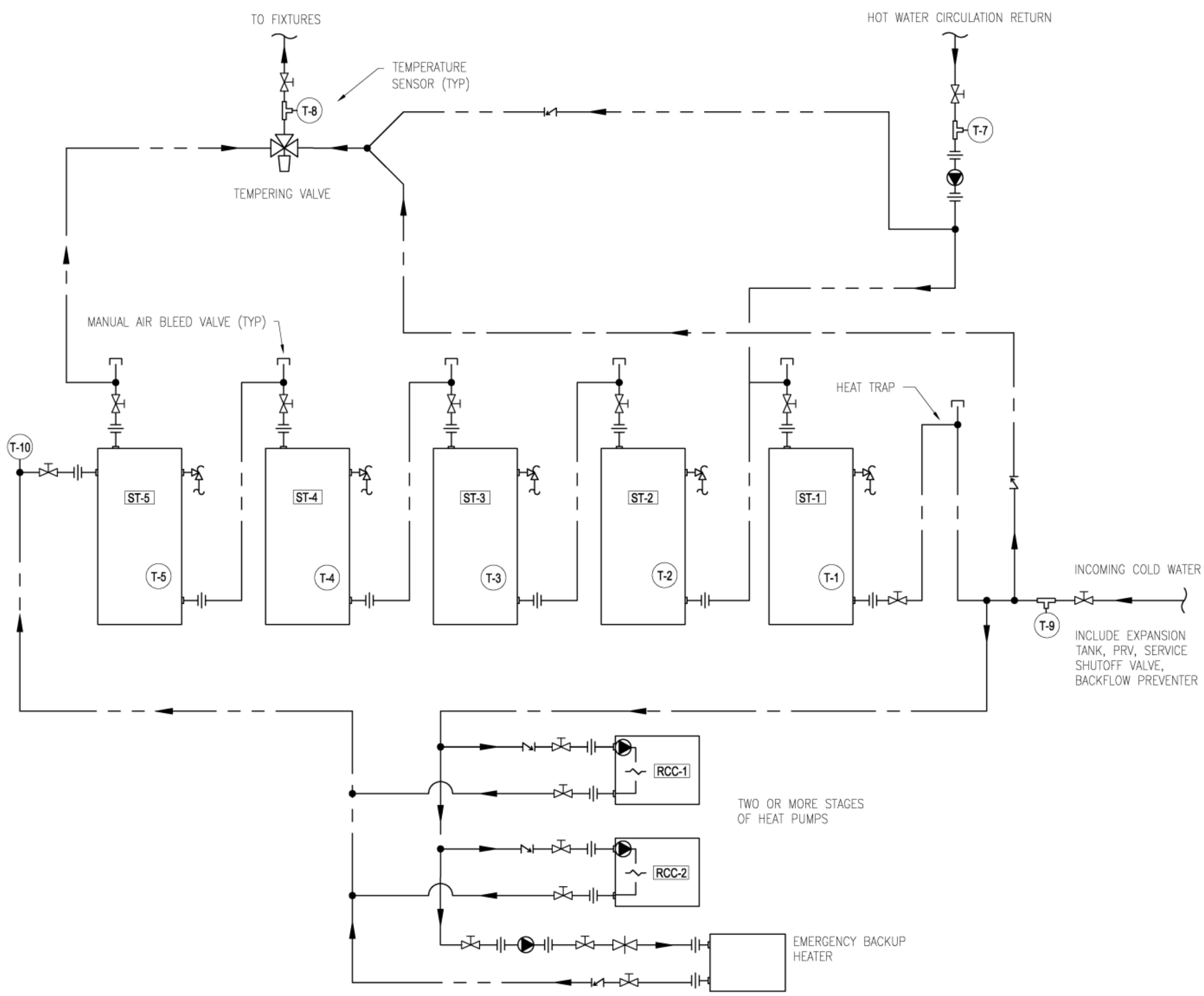

Figure 9: Sample RCC Schematic

An alternate schematic is also included which shows the hot water recirculation loop being treated with a separate heat pump. This configuration adds equipment and complexity to the system, but it avoids some of the problems and inefficiencies associated with bringing hot circulated water back into the heat pump system. An electric heater can be used as an emergency back-up for the circulation loop heat pump to maintain the loop during maintenance events.

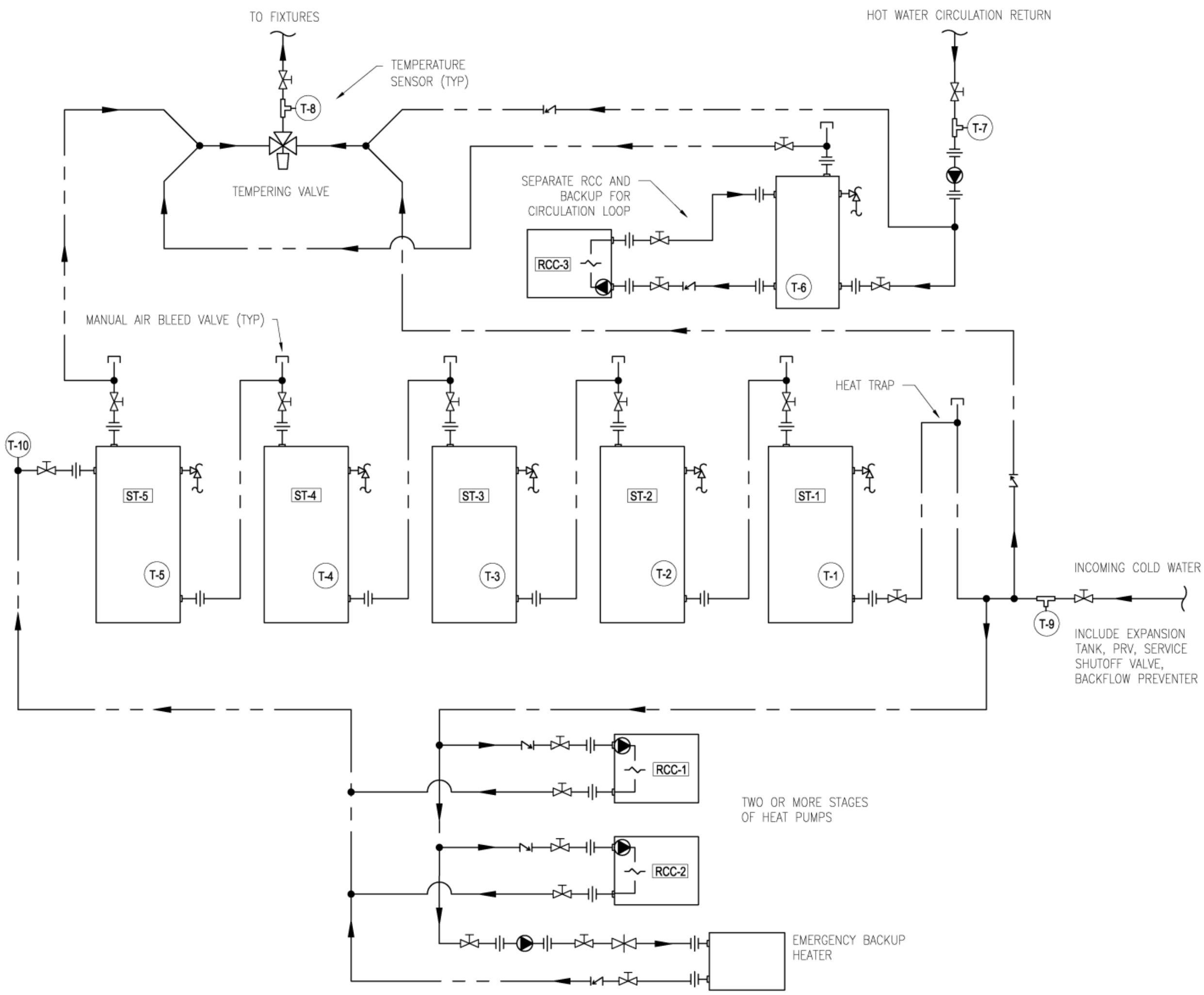

Figure 10: Sample RCC Schematic w/ Dedicated Circulation Loop Heat Pump

Summary of Key Recommendations and Expected Performance

If the basic recommendations of this design guide are followed then performance similar to that measured in the BPA-funded pilot projects can be expected. Heating COPs of greater than this are possible if additional care is taken to optimize the various performance factors discussed above. The key design features needed to ensure a high level of consistent performance include the following:

1. Install RCCs to pull supply air from a below grade parking garage to provide warm air year-round to the RCCs. Vent cold exhaust air to the outside.

2. Set up RCCs to function in “single pass” mode; varying flow through the heat exchanger to deliver a fixed outlet water temperature.
3. Provide multiple storage tanks in series to provide temperature stratified hot water storage.
4. Use ASHRAE sizing methodology outlined in the 2015 ASHRAE Handbook: HVAC Applications, Chapter 50 to size total storage and heat pump capacity.
5. Provide multiple stages of water heating equipment arranged in parallel and stage them in a lead/lag configuration. Provide controls to prevent short-cycling of compressors.
6. Provide full insulation on all distribution and recirculation piping to limit heat loss from the piping system. Eliminate all thermal bridging at piping supports. Provide insulated water tank jackets for storage tanks.
7. Consider inclusion of a separate small heat pump water heater to maintain the temperature of the recirculation loop. Do not use electric resistance or gas fired equipment for hot water circulation reheating.
8. If back-up (gas or electric resistance) equipment is used, configure for emergency only operations.
9. Optimize the performance of all of the components of the RCC system such as compressors, heat exchangers, pumps, and fans. Select a combination of fans and pumps using no more than 150 Watts per nominal ton of RCC capacity.
10. Include basic alarm notifications and measurement and verification equipment to allow for monitoring and troubleshooting of system performance.

In apartment buildings heated with electric resistance space heating a typical RCC installation following these general guidelines can be expected to reduce the required energy use of the hot water system by approximately a factor of 2.6.