Interim Report and Preliminary Assessment of Rheem EcoSense HP50 Heat Pump Water Heater

12 July 2011

Prepared for
Bonneville Power Administration
Contact: Kacie Bedney, P.E.

Prepared by
Ben Larson, Ecotope Inc.

Contract Number 44717

Interim Report and Preliminary Assessment of Rheem EcoSense HP50 Heat Pump Water Heater

Residential Heat Pump Water Heater Evaluation Project

Prepared for:

Kacie Bedney

Bonneville Power Administration

Prepared by:

Ben Larson, Ecotope, Inc.

12 July 2011

Revision 2

Revision History

Rev #	Date	Details of Change	Reason
0	3-16-2011		First release
1	4-27-2011	Revised Table 2 and discussion on 1st hr and EF rating explaining both "simple" EF and DOE method EF calc.	Corrected error in 1st rating. Completed full DOE method EF calculation for 24hr test.
2	7-11-2011	a) Updated resistance element power rating in Table 1. b) Revised bulleted conclusions in observations sections regarding tank storage capacity and efficiency.	a) Based on discussion with manufacturer b) Clarified role of tank storage capacity and heating output capacity

Introduction

Using the measurement and verification (M&V) plan developed by Ecotope to assess heat pump water heaters (HPWH), the Rheem Hybrid HP50 was evaluated at the National Renewable Energy Lab. The M&V plan consists of a series of tests to assess equipment performance under a wide range of operating conditions. The tests include measurement of basic characteristics and performance including first hour rating and DOE Energy Factor (EF), description of operating modes, measurement of heat pump system efficiency and the effects of restricted airflow. For a detailed description of the tests and conditions, refer to the M&V plan document.

This report is the second of three preliminary assessments of three different equipment models. The report is intended as a "first look" at the results and, as such, should still be considered a preliminary assessment. A final assessment will be prepared and delivered later which will include all three HPWH models. This report focuses primarily on the equipment operation and performance itself and not on the interactions with the building in which it is installed.

Basic Equipment Characteristics

The Rheem EcoSense Hybrid, model # HP50RH, is an all electric water heater consisting of a heat pump integrated with a hot water tank. The equipment has two methods of heating water:

(1) by using a heat pump to extract energy from the ambient air and transferring it to the water, or

(2) by using resistance heating elements immersed within the tank.

The heat pump compressor and evaporator are located on top of the tank. A single-speed fan draws ambient air from the top of the unit, through a washable filter, across the evaporator coils, and exhausts colder air out the sides. The refrigerant condenser, which transfers heat to the water is located on the top of the unit unlike the GE or AO Smith models which wrap the condenser coils around the outside of the tank. The HP50 uses a pump to circulate water from the bottom of the tank and pass it through the condenser sitting on top.

The lab conducted a series of measurements amounting to the basic, descriptive characteristics of the equipment. These are given in Table 1 and discussed in the rest of this section. For comparison purposes, the table also shows the values given by Rheem's equipment specification.

As with traditional, electric tank water heaters, the Hybrid HP50 has an upper and lower resistance heating element. Unlike traditional tanks, the elements draw smaller amounts of power, 2.5kW each with a 240V supply. Traditional tanks have 4.5kW elements which operate separately. These smaller elements are allowed to operate simultaneously creating a total equipment draw of 5kW. According to discussions with Rheem, an early version of the HP50 shipped with 2.0kW elements. Subsequent units, and the one tested in the lab, shipped with 2.5kW elements. Both the listed and measured supply voltages are 240V.

The controls for the HP50 are configured to operate the compressor alone or in conjunction with one of the resistance elements. Because the elements only draw 2.5kW, the total power draw of combined compressor and element operation is below that of the equipment maximum. Measurements show the compressor draws 450-1100W depending on both tank water and ambient air conditions. Lower temperatures for both water and air result in lower power draws while higher temperatures result in larger power draws.

Three other components of the equipment also consume power. The most significant is the circulation pump which draws 73W. The fan draws 11W. The control circuits use 8W constantly. Both the pump and the fan are needed for the heat pump system to run whenever the compressor is operational. Additionally, the water heater was found to continue to operate the pump in either its Energy Saver or Normal modes even after the compressor had turned off. This is true with either a single resistance element or both resistance elements operating. The implications for this are discussed later. The fan, however, does shut off when the compressor stops.

The HP50 HPWH is marketed and sold as having 50 gallon capacity but careful measurements showed the unit in the lab held 45.3 gallons. National guidelines on the sizing of equipment allow a 10% variation in nominal versus actual size. This water heater fits within those guidelines albeit on the lower end. This finding is very similar to the GE GeoSpring. It should be noted that the difference in nominal size vs actual size is not unique to HPWHs and occurs with traditional electric resistance tanks as well.

Lastly, the HP50 uses R-410a refrigerant. R-410a is the refrigerant of choice for split-system space conditioning heat pumps but other heat pump water heater manufacturers have chosen to use R-134a in their systems. The refrigerant properties of each have design and operational implications. Most notably, R-410a has a lower condensing temperature than R-134a. This means R-134a systems can heat to a higher temperature. In fact, the HP50 compressor was observed to heat water to ~132°F before shutting off. To heat water any further, the resistance elements are used. R-134a systems heat the tank to 140°F without the need for supplement heat.

Table 1. Basic Characteristics for Rheem Hybrid HP50 HPWH

	Laboratory Measurement	Manufacturer's Specification
Power		
Upper* Element (kW)	2.5	2.5
Lower* Element (kW)	2.5	2.5
Compressor** (W)	450-1100	--
Standby (W)	8	--
Fan (W)	11	--
Pump (W)	73	--
Airflow Path	Inlet on top. Exhaust to sides.	
Airflow (cfm)	100	--
Refrigerant	R-410a	
*240V supply. Elements can operate in tandem.		
**range depends on water T and ambient T. Power increases with both		

Operating Modes and Sequence of Heating Firing

The HPWH has an integrated circuit control board which may be programmed in a number of ways to control when the heating components, compressor or resistance elements turn on and off. Rheem has developed several control strategies, referred to as "operating modes" to determine equipment operation. The Rheem HPWH has three basic modes of operation from which the user may select. They are, in order of most efficient to least efficient:

- "Energy Saver" – combination of compressor and resistance elements
- "Normal" – combination of compressor and resistance elements with the resistance elements turning on more quickly in response to demand than in Energy Saver mode
- "Electric Heat Only" – resistance heat elements only

The M&V plan called for a set of tests to explore the control strategies for the water heater modes of operation. Each test began with the water heaters full of water at a set point of 135°F. A draw was initiated and continued until the compressor turned on (if possible for that mode of operation). The draw was then stopped and the unit was allowed to recover. A second draw was performed for the same air conditions and set point. This second draw was allowed to continue until the electric heaters came on or until 40 gallons of water had been drawn. The units were then allowed to recover. This same procedure was followed for air at 47°F dry bulb, 67°F dry bulb, and 95°F dry bulb, but only the hybrid modes of operation (for the Rheem, this included Energy Saver and Normal modes) were tested at 95°F and 47°F air.

The HP50 can operate its compressor alone or in conjunction with either the upper or lower heating elements. Alternatively, both elements may operate simultaneously but without the compressor. The following observations were made during the operating mode tests.

<u>Energy Saver Mode:</u> When a water draw is initiated and the tank temperature falls, the compressor turns on first. The upper element will subsequently turn on if the tank temperature is too far from set point. Additionally, the compressor may switch off and both elements switch on if evaporator coil frosting occurs, however, both elements rarely operate together in this mode for any other reason. To complete the upper end of the heating cycling (for tank temperatures above 130F), a single element is used to top off the tank. This control strategy favors the operation of the compressor and at most one resistance element unless ambient conditions dictate compressor shut down due to frosting in which case both elements may be used.

<u>Normal Mode:</u> The "normal" mode is similar to Energy Saver except that both electric elements will turn on, independent of coil frosting, to meet high demand situations. When both are on, the compressor is off.

<u>Electric Heat Only:</u> As the name implies, only the resistance elements are used in this mode. For low demand situations, only one element will turn on with the second one coming on as needed. In practice, whether one or both turn on has no impact on overall energy use.

First Hour Rating and Energy Factor

To rank the comparative performance of heat pump water heaters the Department of Energy has established two tests. The first produces a first hour rating which determines how much useable hot water the heater makes in one hour. The second, a 24-hr simulated use test, produces an energy factor (EF) which relates how much input energy is needed to generate the 64.3 gallons of hot water used in the simulated 24 hour period. For tank-type water heaters, the first hour rating depends largely on tank volume and heating output capacity. The energy factor depends on the heating system efficiency and the heat loss rate of the tank. The normative performance characteristics of the equipment are shown in Table 2 and discussed in the rest of this section. Importantly, although the lab carried out the tests in alignment with the DOE specification, the outputs here should not be considered official ratings – those are the ones reported by the manufacturer.

Table 2. Performance Characteristics for Rheem Hybrid HP50

	Laboratory Measurement	Manufacturer's Specification
Tank Volume (gal)	45.3	50
First Hr Rating (gal)	37.5 Energy Saver	67 Energy Saver 72 Normal
Energy Factor, DOE Method	1.69 Energy Saver	2.0 Energy Saver 1.5 Normal
Energy Factor, “simple calc”	1.65 Energy Saver	
Tank Heat Loss Rate (Btu/hr°F)	5.1	--

The lab conducted both the 1-hr and 24-hr tests to demonstrate repeatability with the manufacturer’s data. The tests are conducted in “Energy Saver” mode which is the default setting on the equipment when shipped by Rheem. Both tests were conducted per the DOE specification.

One source of ambiguity in the setup was tank temperature set point. The set point of the unit under test was the highest setting on the control panel. The installation manual lists the tank temperature as 135-140°F. The next setting down in temperature indicated in the installation manual is 130-135°F. At the time of the test, it was unclear which setting the manufacturer used in the rating. The standardized DOE setpoint is 135°F ±5°F. Therefore, either setpoint would be within the tolerance limit of the test. However, it is highly likely that the manufacturer’s rating test used the lower setpoint as this would lead to higher performance values. Importantly, the starting tank temperature average was 130.7°F for the 1hr test and 134.8°F for the 24 hr test which are both within the test method tolerances.

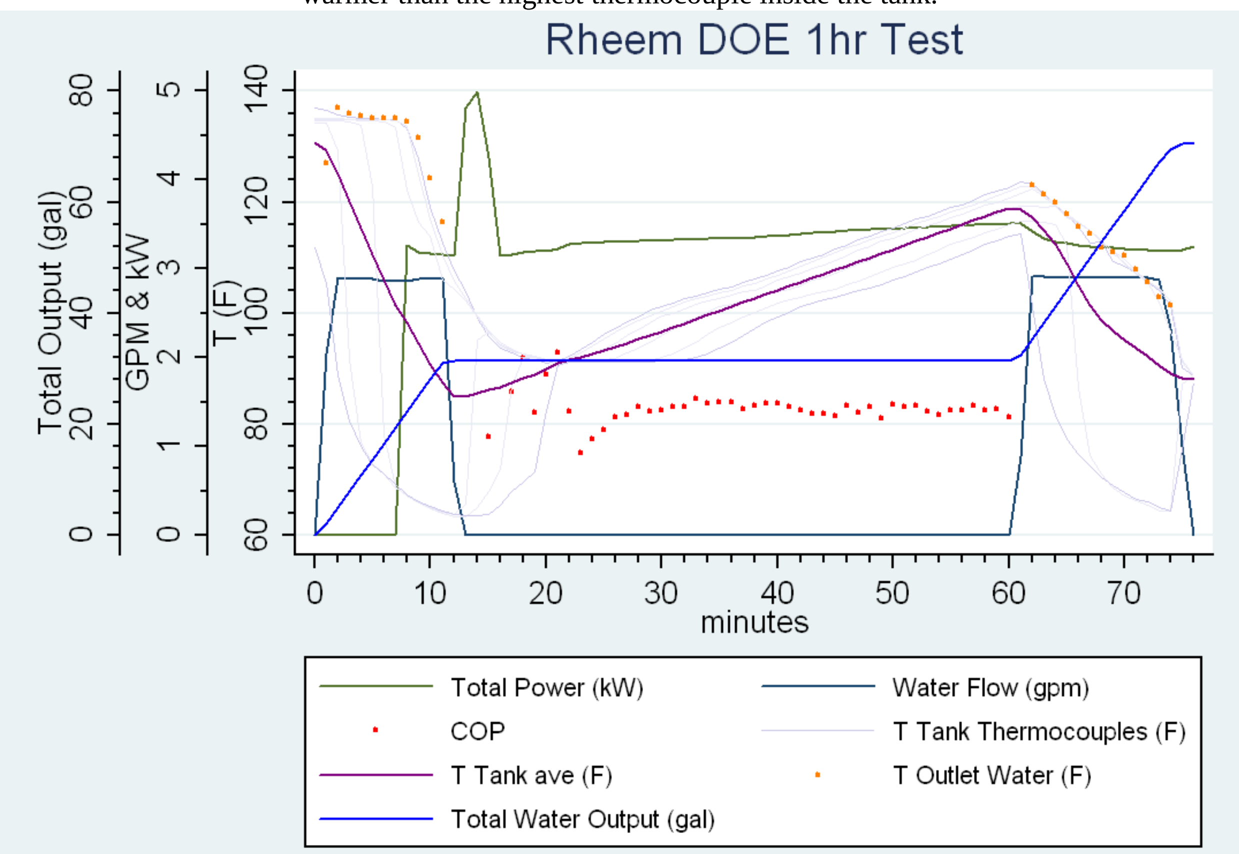
For the Rheem HP50, the use of the higher set point is expected to show up as a penalty in the EF calculation because the resistance heaters need to be used longer to top off the higher tank temperature. For the 1 hr rating, subsequent discussions between the manufacturer and the lab determined that Rheem conducted its 1hr rating using the lower, ‘hot’ setting. This triggers special controls inside the equipment which are designed to optimize the result of the 1hr test. The difference in settings is likely to explain the difference in values for the 1 hr rating.

The data from the one hour test are plotted in Figure 1. Approximately 7 minutes into the first draw, the heat pump and one element turn on (green line showing 3.2kW). The resistance element is drawing 2.5kW while the heat pump system (compressor, pump, and fan) draws 700W. At 13 minutes, just as the outlet water temperature has fallen 25°F, the first draw is terminated and the second resistance element turns on (green line spike to 5kW). The compressor momentarily shuts off but the pump stays on. At 16 minutes, the second element has shut off and the compressor starts to operate again in tandem with the first resistance element.

The equipment coefficient of performance (COP) is shown by the red squares on the plot. Starting near 30 minutes, the tank temperature and equipment reach steady conditions and the COP settles into a nearly flat line. The COP is calculated on minute to minute time steps and includes the total equipment power draw (compressor, pump, fan, controls, and resistance elements). For the majority of the test, the COP is near 1.5. This reflects the combination of resistance heat at COP=1, and the heat pump system at COP≅3 for tank temperature at 105°F and ambient temperature at 67.5°F (DOE test conditions).

Figure 1. DOE One Hour Test.

The dark blue line shows the prescribed water draws at a 3gpm flow rate. The bright blue line shows the cumulative water drawn during the test. The green line plots the total equipment power consumption. The thick purple line displays the average tank temperature while the thin lavender lines show the temperatures reported from the six thermocouples placed at different heights (corresponding to equal volume segments) within the tank (in effect a temperature profile of the tank at any point in the test). The red dots, plot the minute-to-minute COP. Lastly, the yellow dots plot the output water temperature. Output water temperature is always just slightly warmer than the highest thermocouple inside the tank.



The 24-hr simulated use test consists of six, 10.7 gallon draws equally spaced over six hours followed by 18 hours of standby. The standard test conditions are 67.5°F, 50% RH ambient air, 135°F tank set point and 58°F incoming water temperature. As previously discussed, this test used the 135-140°F set point on the equipment. As with the first hour rating, the heater operating mode was set to Energy Saver. Figure 2a shows the first six hours of the test so the draw events and recovery can be examined in more detail. Figure 2b shows the full 24 hours which also demonstrates the tank heat loss rate.

At the most basic level, an energy factor is the ratio of total useful energy output to total energy input. In the any test, the tank may start and end at different average temperatures (energies) so that must also be taken into account in the calculation. In this 24hr test case, as with the 1hr test, the tank begins with a slug of cold water in the bottom 1/6 of the tank. Although the thermostats are satisfied everywhere else in the tank, this brings the average temperature down. The tank ends the test at a higher average temperature because the pump has been running which completely mixes the tank, including the very bottom.

The Energy Factor (EF) was calculating in two ways: using a "simple" method and the DOE prescribed method. The DOE test method prescribes a standard set of operating conditions to use for the test and for normalization purposes in the calculation of the EF. The "simple" calc divides energy output by energy input and does not normalize to standard conditions. The extent that the simple EF agrees with the DOE method EF, reflects how tightly the lab (and the equipment tested) held to the standard conditions. Both EF calculations are given in Table 2. For comparison to the manufacturer's data, the DOE method EF should be used. By calculating the EF in two ways, we can demonstrate that the lab held very closely to the test tolerances.

The EF of 1.69 compares to the published EF of 1.5 for Normal mode and 2.0 for Energy Saver mode. It is highly likely that the use of the highest water temperature setting on the tank led to the observed reduction in EF. Because the refrigerant condensing temperature limits compressor operation for tank temperatures above 130°F, the resistance elements must operate comparatively longer for the highest set point as opposed to the second-highest. This extra use will pull down the EF. This set point ambiguity was not noticed until the test equipment had already been dismantled so there wasn't an opportunity to rerun the test for a comparison. Nevertheless, it should be repeated that the highest temperature setting was still within the DOE specified tolerances but not at the optimal end of the range.

Figure 2a plots much of the same data as Figure 1. It also shows much more variability in the COP because the equipment switches between compressor only and resistance element only operation. The instantaneous COP is a measure of how much heat is added to the hot water in a given time interval divided by the energy used to create or deliver that heat in that interval (in this case one minute). For electric resistance heat, the COP is generally assumed to be 1. In contrast, the COP for heat pumps can vary greatly depending largely on the ambient air conditions (heat source) and the tank temperature (heat sink). More discussion of the COP occurs later. The scatter in the COP plots is due to uneven, short-term fluctuations in the tank temperatures but the general trend is clear. For the compressor use in the test, green line at 1.1kW, the COP is around 2.0. For the resistance element only use, the COP shows up as less than one because the pump, using energy that doesn't add to the water (the lab reported the pump housing was hot to the touch during operation), continues to run, and the tank is losing heat to the ambient air at a rate of about 90W. Both of these effects are also present for compressor only operation.

Figure 2a. DOE 24hr Simulated Use Test.
First 6 hours of test covers all six draws and full tank recovery.

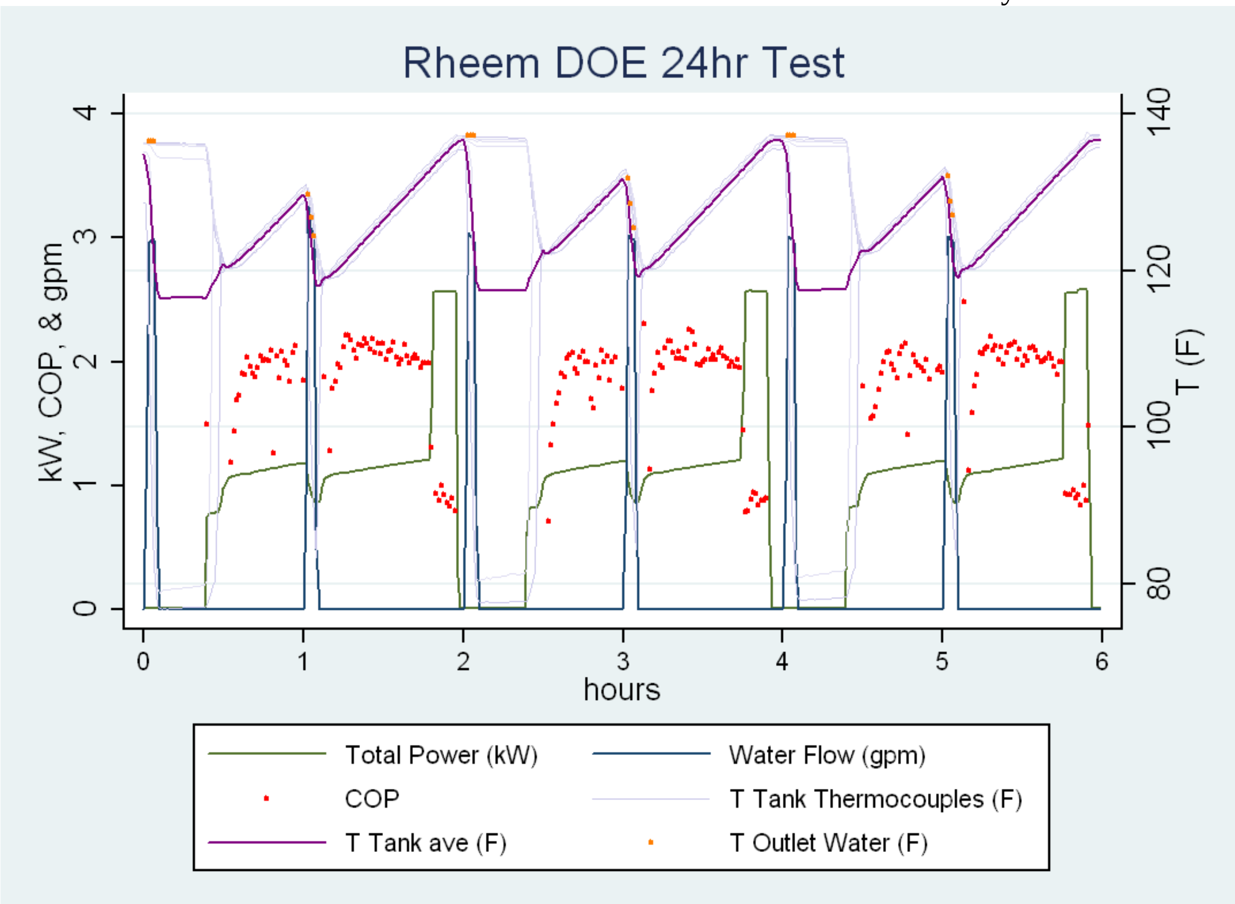


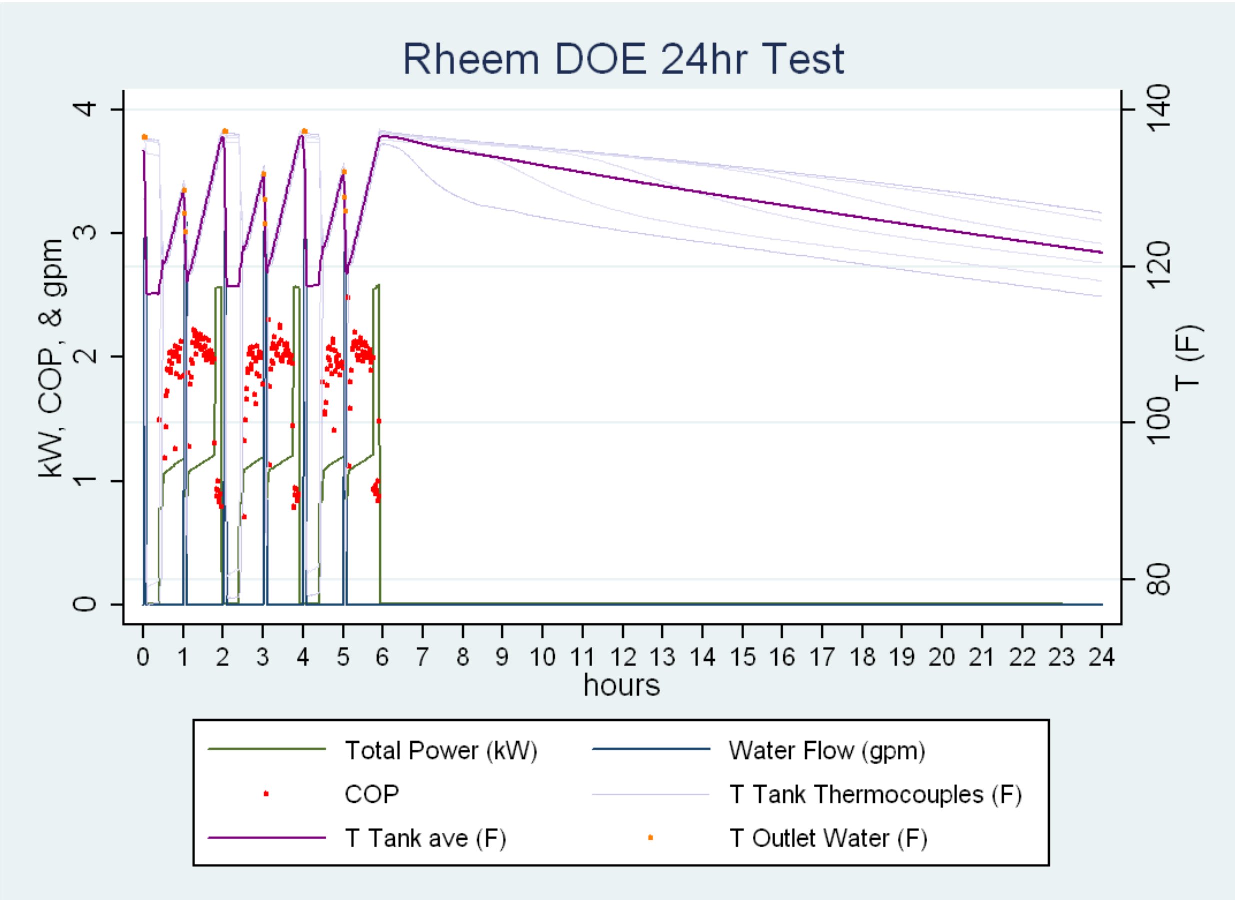
Figure 2b shows the full 24hrs of data. From hour 6 for the remainder of the test, the tank is in standby mode with the only power draw being 8W for the control circuits. From the change in average water temperature over this period, a heat loss rate of 5.1 Btu/hr°F (1.5 W/°F) was calculated for the tank. For a tank installed inside a house with a set point of 120°F, this heat loss amounts to 657 kWh/yr. If installed in a garage with an average year round temperature of 50°F, the losses amount to 920 kWh/yr. Unlike traditional electric tanks which recover the standby loss with a COP of 1, Figure 2b shows the Rheem HPWH, using the compressor, will recover standby losses with a COP of 2 thereby reducing that portion of annual energy use by half.

One striking feature of Figure 2b is that the water heater performs no standby firings during the test. Instead, it lets the average tank temperature fall from 136°F to 121°F. Judging by the temperature of the bottom two thermocouples, the tank is likely to turn on again in the one to two hours following the test.

Next, the heat loss rate of the equipment was only calculated when the systems were off. This will apply to all standby periods but not when the circulation pump is running. The pump draws water from the bottom of the tank and up a pipe outside the insulated envelope of the tank.

During this transit, the water will exchange additional heat with the surroundings. While there was no lab data available to quantify this heat loss potential, the equipment COP calculation does take it into account. The COP of the compressor operation is calculated using the change in temperature of the tank compared to the energy input during a given time interval. The temperature change in the tank will be comparatively decremented while the pump is running thereby reducing the COP for that interval.

Figure 2b. DOE 24hr Simulated Use Test. Full 24 hours of test.



Equipment COP and Operating Range

To fully understand the HPWH performance, the M&V plan called for a mapping of equipment COP at varied tank temperatures and ambient air conditions. These COP measurements reflect how efficiently the heat pump components of the HPWH are operating under any given set of conditions. These COP calculations do not apply when the resistance elements are operating, in which case the COP is 1. The performance map is extremely useful in understanding how well the equipment will operate in a conditions encountered in garages and unconditioned basements. The COP tests start with a full tank of cold water and the equipment off. The equipment is then switched on in compressor only mode and data is recorded as the tank heats up to set point. This is repeated for a set of ambient conditions. The test conditions are given in Table 3.

Table 3. Test conditions for COP Mapping

Test Name	Ambient Air Conditions					Inlet Water		Outlet Water	
	Dry-Bulb		Wet-Bulb						
	F	C	F	C	RH	F	C	F	C
COP-47	47	8	43	6	73%	35	2	135	57
COP-57	57	14	50	10	61%	35	2	135	57
COP-67	67.5	20	57	14	50%	35	2	135	57
COP-77	77	25	61	16	40%	35	2	135	57
COP-85	85	29	68	20	42%	35	2	135	57
COP-95	95	35	75	24	40%	35	2	135	57
COP-95 dry	95	35	66	19	20%	35	2	135	57
COP-105	105	41	84	29	42%	35	2	135	57
COP-105 dry	105	41	69	21	16%	35	2	135	57

The HP50 is design to use the resistance elements only to heat the tank when the water temperature is below 80°F. Therefore, in order to measure performance of the compressor, per the suggestion of Rheem, the lab provided an override control of the system by installing operator adjustable "temperature sensors." These are actually potentiometers used to send artificial temperature signals to the control board in order to get the compressor to run regardless of tank temperature. For actual installs in houses, the compressor would never run under these circumstances but this procedure allows the full characterization of the heat pump system. Artificially extending the compressor operating conditions also serves to produce better curve fits for an equipment performance model.

Operating Range

In addition to operating condition limits due to the water temperature, the lab observed operating limits due to ambient air conditions. For instance, the 47°F test proved to be too cold for sustained compressor operation. Under these conditions (for all water temperatures), the HP50 detects potential icing on the coils and turns the compressor off. The resistance elements both turn on for approximately 2 minutes. Then compressor will turn on again for 5 minutes and, if potential coil frosting conditions are detected, will cycle off again. The compressor is allowed to cycle 3 times before it is shut off in favor of the resistance elements for the rest of that particular heating period. The limits to the heat pump operation are summarized as follows:

- At the COP47 conditions, for all water temperatures, the compressor cycles three times and then stops operation letting the resistance elements take over.
- At the COP57 conditions, the compressor attained sustained operation in the range of 115-123°F water but not for colder water temperatures.
- For the warmer COP67 conditions, the compressor operated steadily for all tank temperatures above 62°F.
- For the COP77, 85, 95, and 95dry conditions, the compressor operates without cycling off for frosting events.
- For the COP105 and 105dry conditions the compressor did not operate at all. Instead, the equipment blinked a fault code which indicates that the difference between suction and discharge temperatures in the refrigerant loop was less than

35°F. It's not clear what problem that fault is preventing or if that fault code is related to the reasons why the compressor would not run.

Given the spread in testing conditions, the temperature range of sustained compressor operation cannot be determined to within 1°F precision, but the cut off points can be estimated from the data. On the low end, it is likely the compressor will not run continuously for ambient temperatures below 60°F (the humidity ratio of the air will change it somewhat). At the high end, the compressor will not run above 105°F (the cutoff will likely be less than that). These findings differ from the manufacturer's information which shows a heat pump operating range of 40-120°F (Rheem HPWH Technical Webinar 1.26.2010).

The implications of limited compressor operation are significant for water heaters installed in cool, non-conditioned spaces. For ambient temperatures below 60°F, the heat pump will not operate very long (less than 15 minutes in every heating cycle) and the water heater will perform largely like an electric resistance tank. The high temperature limit is not of concern for most Pacific Northwest conditions. Additionally, the added space cooling the HPWH provides will act to keep the space temperature reduced.

Equipment COP

Equipment efficiency is dependent on the water temperature in the tank, ambient air temperature, and ambient air moisture content. Figure 3 shows the change in COP with average tank temperature, a decreasing COP for increasing water temperatures, for the various tests. The curves in the plots are logarithmic fits to the measured data.

Figure 4 shows the COP dependence on ambient air dry bulb for a set of given tank temperatures. The COP actually depends on both dry bulb and wet bulb temperatures but, for simplicity, the wet bulb dependence is not shown in the plot. The fact that analysis of the test data shows dependence not only on wet bulb but also on dry bulb temperature suggests that the tests measured a difference in latent heat removal at the different testing conditions. Using regression techniques, the performance map was turned into a function so that efficiency can be predicted at any set of conditions.

$$COP = -23.86 - 0.024*Tdb + 0.326*Twb + 5.934*\ln(Twb) + 1.029*\ln(Ttank) - 0.0723*\ln(Ttank*Twb)$$

where Ttank = average tank temperature (F)
Tdb = ambient air dry bulb temperature (F)
Twb = ambient air wet bulb temperature (F)

Further implications of heat pump performance will be explored in later reports. Moreover, the functional form of the current COP curve has many terms compared to the GE water heater model. An attempt will be made to simplify the fit.

Figure 3. The plotted lines are fits to measured data.

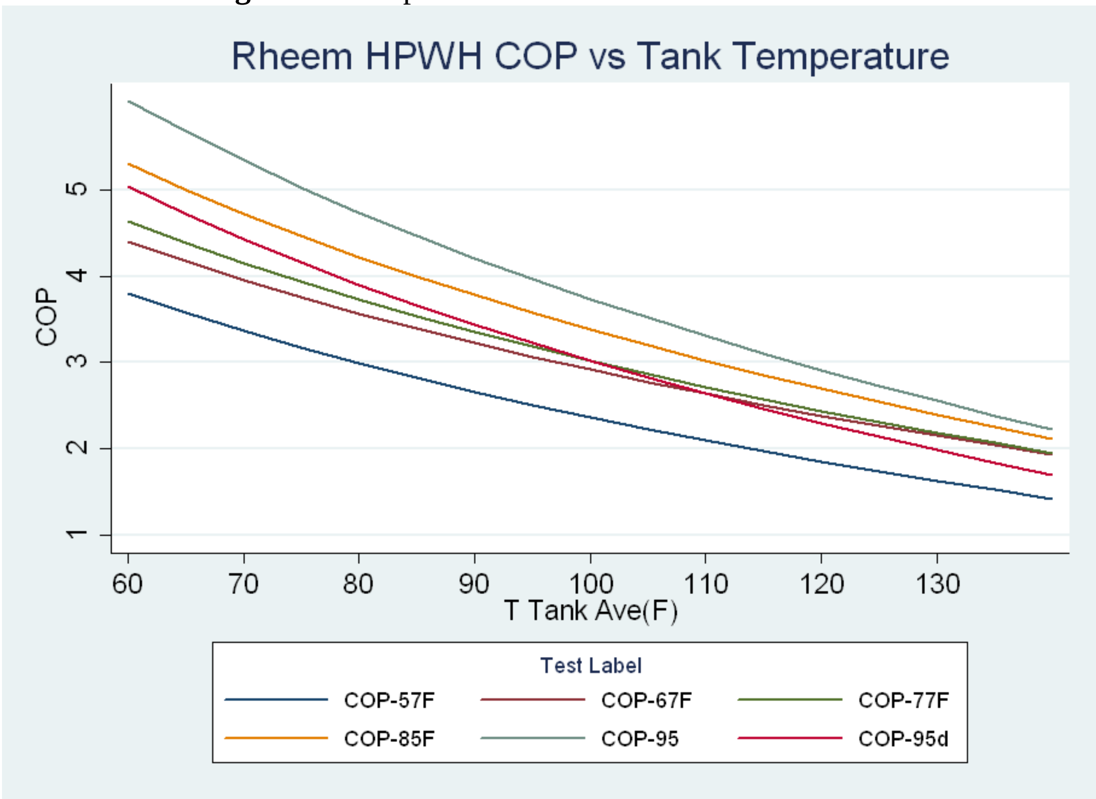
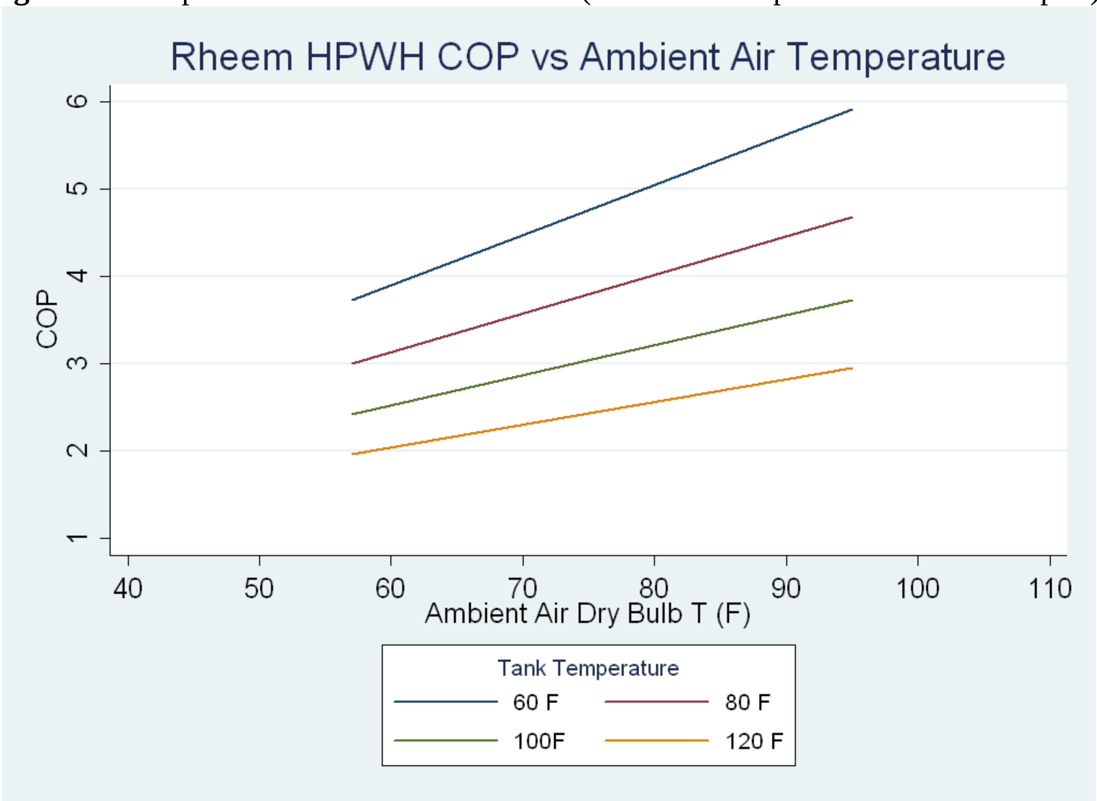


Figure 4. The plots are fits to measured data. (COP-95d test point excluded from plot).



Air Flow Effects on Performance

To evaluate the effect of reduced airflow on the equipment operation, two tests were conducted. The filter area was restricted by 1/3 and 2/3 of its surface area for the measurements. The COP-67 test was then carried out. The analysis shows no substantial change in performance for the test with 1/3 of the filter blocked. Curiously, the measured airflow increased from the standard 100 cfm with no blockage to 125 cfm for this case although the fan power remained constant in both cases. The 2/3 blockage test shows different results with a marked degradation in performance. The airflow for this case drops to 78 cfm and the COP is reduced anywhere from 16% at 80°F tank temperatures to 8% at temperatures near 130°F. These findings indicate that the system will still operate well with some amount of dirt on the air filter. In contrast, a very dirty filter is likely to start reducing performance by 10-15%.

Draw Profile, Pump Mixing, and Capacity

In addition to the standard DOE 24-hr draw profile, two supplement draw profiles were conducted to observe the water heater under a wider range of potential, real-world, conditions. The first draw profile, referred to as DP-2 in the M&V plan simulated a heavy water use pattern targeting 110 gallons of water per day. The conditions used for DP-2 include: EnergySaver mode, 120°F set point, 67.5°F ambient temperature, and 45°F inlet water (to simulate winter seasonal mains temperatures).

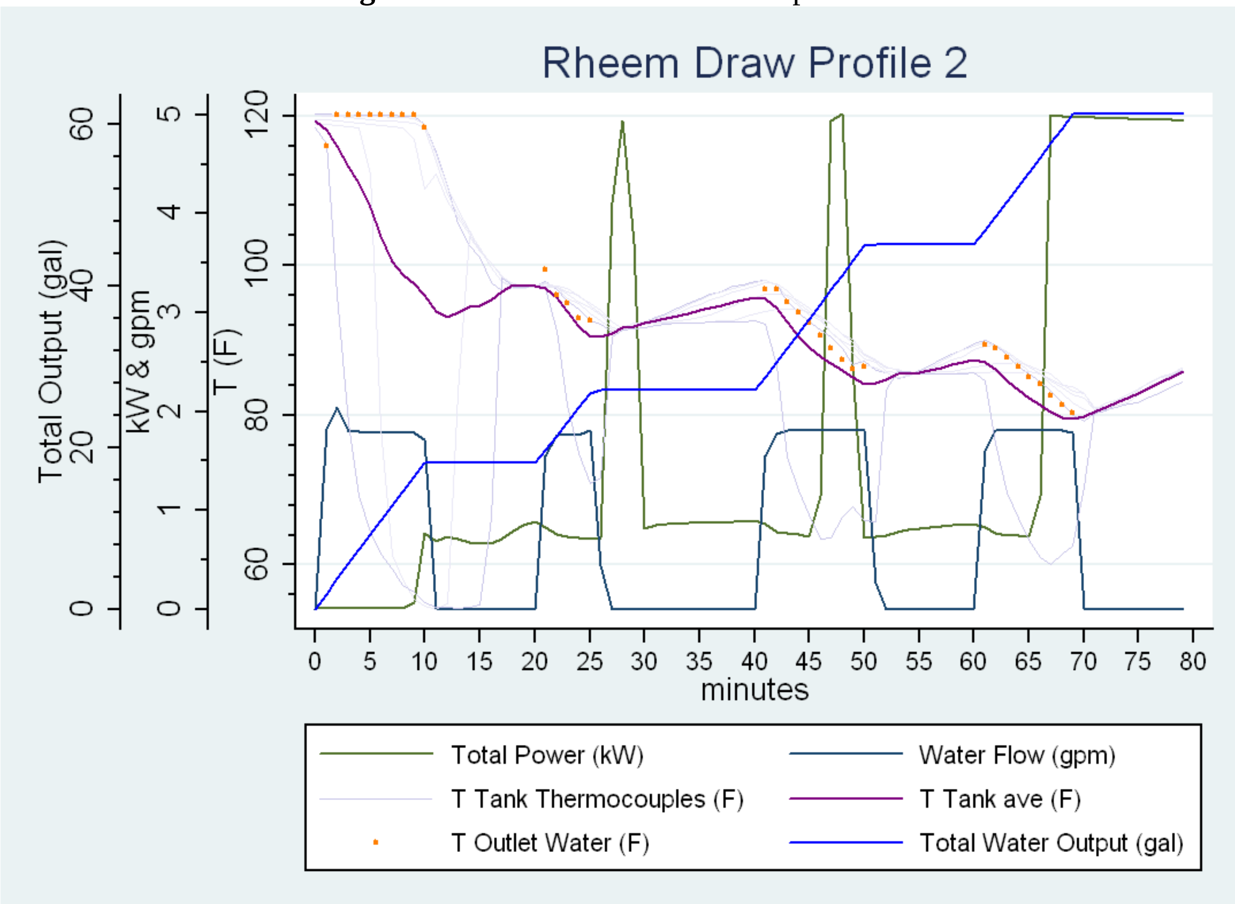
The results of running the profile show that the water heater lacks enough capacity (both storage and energy output) to meet the load imposed by this test. This finding doesn't necessarily indicate a shortcoming of the equipment, rather it suggests a larger water heater is the correct size for the load. It is highly unlikely a designer or plumber would choose to install such a small water heater for a high demand application (active family of four).

The tank capacity aside, data from DP-2 highlight a potential, real problem with the equipment design. The operation of the circulation pump acts to mix the water in the tank well. It has the undesirable side effect of destratifying the tank which mixes the cold inlet water at the bottom, with the useable, hot water at the top. Figure 5, which shows the first 80 minutes of DP-2, illustrates the process. The first draw of 18 gallons begins at minute 0 and lasts through minute 10. When the draw stops, the outlet water temperature is just below 120°F. The compressor *and pump* turn on at minute 9 and begin mixing the tank. The mixing effect can be seen in the continued decline of the water temperature at the top of the tank (upper-most thin lavender line). By minute 20, when the next draw begins, although the heater has been adding heat to the tank, the outlet water temperature has dropped to below 100°F. By the end of the second draw, an additional 10 gallons has been used and the outlet temperature has fallen to 92°F. Depending on the specific end use, it is highly likely that any outlet temperature below 100°F is not useable especially when pipe losses are considered. The decline to 100°F only happened in a single 18 gallon draw, while the next draw quickly drops the temperature further.

In EnergySaver mode, the tank is operating primarily with the compressor and not with the aid of one of the resistance elements. If one of these elements were to turn on and add more heating capacity, it is still likely to not make enough of a difference in the outlet temperature. The main cause of the drop is the mixing of cold inlet water with the useable water at the top which happens whenever the compressor runs. Further, even if both elements are used and the pump is not needed, it will still run unless the equipment has been switched to "Electric Heat

Only" mode. In the end, the presence and operation of the circulation pump is likely to make hot water unavailable for significant periods of time in any of the efficient heat pump modes for all but the lightest water use patterns.

Figure 5. First 80 minutes of draw profile 2.



Observations on Equipment Design

The last section in the report discusses observations on the equipment design and their implications for operation and performance.

- First, the tank appears to be sized too small in order to take full advantage of the efficiency of heat pump heating. All electric tanks, as compared to gas, have traditionally had lower heating output capacities so are sized larger. Likewise, HPWH heating output, especially at colder temperatures, can be lower still than the resistance elements, suggesting a larger tank is warranted in order to use compressor heating more of the time. This tank, at 45.3 gallons, using its most efficient modes is likely to meet the needs of only light to medium hot water use households. The hot water demands of larger households can be met but they are likely to come at the expense of efficiency. To meet the high demand periods, the water heater will switch back to operating like a resistance element tank. The alternative to not switching to resistance heating is compromised output water delivery temperature. Therefore, for higher water loads, larger tanks are likely to offer the advantage of reduced energy use while maintaining comfort. With more storage capacity, it is likely a tank will be able to heat water more of the time with the heat pump.

- The compressor capacity is reasonably sized, and, in any case, larger than that used in the GE HPWH. This has the advantage of providing more heat more quickly to the water in heat pump mode. An even larger compressor size could provide an efficiency improvement alternative to sizing a larger tank. However, the space constraints of house installations and the general geometry of the equipment provide practical upper limits on component layout and size.

- In contrast to the large compressor capacity, the airflow and evaporator coil design appear to be mismatched. For even mild ambient conditions (air temperatures in the low 60s and below), the coil temperature drops quickly to a range which could induce frost buildup. This forces the compressor to cycle off for a defrosting period. There is no active defrosting so the equipment just waits for the coils to warm up again. While waiting, it uses resistance heat.

- For operation in the Pacific Northwest, the compressor has too narrow of a temperature range. It is limited to approximately 60-100°F. With this narrow ambient temperature range, locating the technology in a buffer zone is likely to result in significantly reduced operating efficiencies. The compressor could operate unencumbered in conditioned spaces but that also incurs more of a heating system interaction penalty All buffer install locations are likely to spend the majority of the time operating in resistance only mode.

- Next, by using a circulation pump in the design of the equipment, the applicability is seriously limited. Mixing the water in the tank is generally undesirable from a user's perspective. Once a large draw has begun, the cold water mixes in with the existing hot water to lower the outlet temperature. For tanks that don't mix and remain stratified (a traditional electric or gas water heater), the outlet temperature stays high until most of the tank water has been replaced. As was demonstrated in draw profile two, the mixing will reduce the hot water delivery temperature to an unacceptable level, leading to user dissatisfaction. The first major water use will always be hot but the second significant use, after tank mixing has begun, will be colder. Extremely low water users may find the outlet water temperatures acceptable but other users are likely to encounter undesirable periods of cold water.

- The control panel offers a simple interface for changing settings, however, the water set point control does not show temperatures. Instead, it has a gradient between Hot, Normal, and Vacation. The owner must reference the manual to learn what setting is required for 120°F water.

- Lastly, the equipment operating modes theoretically offer a reasonable mix of strategies to meet efficient or high demand scenarios. Allowing both the compressor and upper element to run, as is possible in EnergySaver and Normal mode, is an optimal way to produce hot water quickly while still maintaining improved energy performance. In practice, however, the compressor operating range and circulation pump limit the usefulness of this operation. In the end, these operating characteristics are likely to lead to both reduced energy savings and user experience for installations in the Pacific Northwest.