Laboratory Performance Evaluation of Residential Integrated Heat Pump Water Heaters

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National Renewable Energy Laboratory

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Technical Report
NREL/TP-5500-52635
Revised June 2014

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Prepared under Task Nos. WTN9.1000 and ARRB.2204

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Note

The work presented in this report does not represent performance of any product relative to regulated minimum efficiency requirements.

The laboratory and/or field site used for this work are not certified rating test facilities. The conditions and methods under which products were characterized for this work differ from standard rating conditions, as described.

Because the methods and conditions differ, the reported results are not comparable to rated product performance and should only be used to estimate performance under the measured conditions.

About the Revision

This report was revised in June 2014 to clarify that the rated performance of a water heater can only be determined at certified ratings laboratories.

Executive Summary

The residential integrated heat pump water heater (HPWH) is an emerging technology that provides cost-effective energy savings compared to legacy products in domestic water heating. The heat pumps in these units are small refrigerant-based direct expansion systems, which absorb energy from the surrounding air and transfer it to water in an attached tank. This type of system is expected to have a high coefficient of performance (COP)—the ratio of the useful energy transferred to the electrical energy consumed— across wide ranges of operation. Electric resistance water heaters have a COP of nearly 1.0, but HPWHs are expected to provide annual COP values over 2.0. While HPWHs are not a new concept (the first HPWH was developed in the 1950s), several major water heater manufacturers have recently developed integrated HPWH models, meaning that the heat pump and water tank come as a packaged unit with backup electric resistance elements.

Researchers at the National Renewable Energy Laboratory (NREL) evaluated five integrated HPWHs in a laboratory setting to determine their performance in a range of ambient conditions and under different levels of use. The results describe how these products function, demonstrate that efficient operation is typical but limitations exist, and provide information to determine reasonable expectations for the products. The performance testing was conducted at NREL's Advanced Thermal Conversion Laboratory, which is configured for high-accuracy performance measurement of thermal conversion systems.

Four sets of tests were performed on each HPWH: operating mode tests, draw profile tests, performance-mapping tests, and reduced airflow tests. The operating mode tests were designed to tease out the control logic for each operating mode. The HPWHs had at least three operating modes: Heat pump-only mode, Hybrid mode, and Resistance-only mode. Hybrid mode uses the heat pump and backup resistance elements to balance the efficiency of the unit with the need for hot water, and the controls in this mode varied significantly between the different units. The draw profile tests subjected the HPWHs, while in Hybrid mode, to a simulated-use draw profile. The results from the draw profile tests were used to calculate system COP values for the HPWH running as a complete system. The performance-mapping tests were conducted under a number of different conditions ranging from a dry bulb temperature of 8°C to 40.5°C. Only the heat pump was allowed to heat the tank. These tests produced curves that determined the efficiency of the heat pump based on both the ambient air conditions and the average temperature of the water tank. The last set of tests evaluated how restricting the air flow to the HPWH, as may happen with a dirty filter, would affect performance.

In general, all the HPWHs were very efficient in their typical operating range, with performance improving in warmer conditions. In colder conditions, performance goes down but the HPWHs are still more efficient than a standard electric water heater. The low temperature cutoff for heat pump operation is generally 45°F, and below that temperature the electric resistance elements are used exclusively. Comparisons of the heat pump COP from the performance-mapping tests and system COP from the draw profile tests are given below.

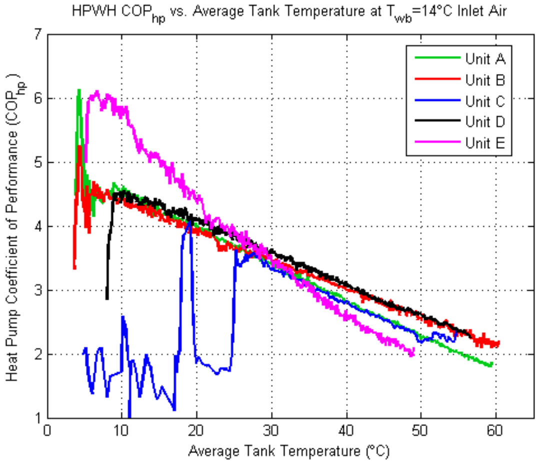

Figure ES-1. Comparison of heat pump COP curves in 14°C wet bulb ambient air

Table ES-1. Comparison of System COP from Draw Profile Tests

	COP$_{sys}$	
HPWH Mfr.	**High Use (Morning)**	**Low Use (Evening)**
Unit A	3.55	3.42
Unit B	1.21	1.81
Unit C	1.44	2.61
Unit D	3.85	5.37
Unit E	1.68	2.77

Some other factors that play into the performance of the HPWHs are the tank size and control logic. Two of the units tested had 80 gallon tanks, which allowed them to use their heat pump more, even in times of high demand. The control logic that determines when the backup resistance elements will be used can also have a big impact on performance. For instance, units that had a temperature sensor low in the tank could trigger the heat pump to turn on early in a draw, rather than waiting until the middle or top of tank filled with cold water. Tank size and control logic both play into the balance between efficiency and available hot water, as HPWHs have a slower rate of recovery if they are operating efficiently. Choosing the correct tank size and selecting an appropriate combination of set point and operating mode will ensure sufficient hot water and significant reduction of water heating energy consumption.

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List of Figures

All figures in this report were created by NREL.

List of Tables

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Definitions

Acronym	Definition
AC	Alternating Current
COP_{hp}	Coefficient of Performance of the Heat Pump
COP_{sys}	Coefficient of Performance of the System
DC	Direct Current
DOE	Department of Energy
DX	Direct Expansion
EPA	Environmental Protection Agency
HPWH	Heat Pump Water Heater
ORNL	Oak Ridge National Laboratory
SHR	Sensible heating ratio
WFO	Work for Others

Introduction

Advanced technologies for residential buildings are sought that provide broadly applicable, measurable, and cost-effective energy savings compared to legacy products. One significant opportunity for energy savings is domestic hot water heating, where an emerging technology has recently arrived in the U.S. market: the residential integrated heat pump water heater (HPWH). The heat pumps in these units are small refrigerant-based direct expansion (DX) systems, which absorb energy from the surrounding air and transfer it to water in an attached tank. This type of system is expected to have a high coefficient of performance (COP), which is the ratio of the useful energy transferred to the electrical energy consumed, across wide ranges of operation. Electric resistance water heaters have a COP of nearly 1.0, but HPWHs are expected to provide annual COP values over 2.0.

The development of the HPWH began in the 1950s, when the Hotpoint Company, which later became a division of General Electric (GE), designed and built a HPWH intended for mass production (Calm 1984). The technology performed well, but was stricken with reliability issues. In the end, development efforts ceased because energy prices were low and there was little demand for the product. Fueled by rising energy prices in the 1970s, HPWH products re-emerged, this time backed with improved heat pump technology. Oak Ridge National Laboratory (ORNL) tested both add-on and integrated units in 1982. Add-on HPWHs have a heat exchanger that is pushed into an existing hot water tank, often through the drain port. Integrated HPWHs are factory integrated with a water tank and backup resistance heating elements. ORNL's field and laboratory testing showed that HPWHs use about half the energy to heat domestic hot water when compared to an electric resistance water heater (Levins 1982).

Despite this promising research, few HPWHs were sold once energy prices fell sharply in the 1980s. It was not until the turn of the century that a resurgence in the technology began again. An Australia study in 2001 used a TRNSYS model based on test results from three HPWHs to show that the annual COP for an integrated HPWH was 2.3, which translated to annual energy savings of 56% (Morrison 2003). The technology was market ready, but a 2004 study identified cost, consumer awareness, and contractor technology perceptions as barriers to market acceptance in the United States (Ashdown 2004). Meanwhile, foreign markets embraced the technology. For example, models such as the EcoCute became prevalent in Japanese markets (Hashimoto 2006).

Backed by the U.S. Department of Energy (DOE) and the Environmental Protection Agency (EPA), integrated HPWH technology was added to the ENERGY STAR® program in 2008 (CEC 2011). This encouraged key manufacturers to revisit integrated HPWHs, resulting in those now available on the U.S. market.

In this report, we present a laboratory evaluation of the five integrated HPWHs available in the U.S. market today. The results describe how these products function, demonstrate that efficient operation is typical but limitations exist, and provide information so reasonable expectations for the products can be determined. Performance testing occurred at the National Renewable Energy Laboratory (NREL) Advanced Thermal Conversion Laboratory, which is configured for high-accuracy performance measurement of thermal conversion systems and was used to explore HPWH performance across the full range of operating conditions.

Test Plan

The test plan for this project can be broken down into four sections. A summary of this test plan can be found in Table 1 and includes the air and water conditions, and operating modes associated with each test run during this experiment. The test plan was originally written by Ecotope, with a few additional tests added by NREL, and the complete list of tests performed is shown in Table 1. Following the summary are detailed descriptions of each of the tests that were performed.

Five integrated HPWHs were tested: the A. O. Smith Voltex hybrid electric HPWH, the GE GeoSpring water heater, the Rheem Hybrid Electric water heater, the Stiebel Eltron Accelera 300 HPWH, and the Air Generate AirTap Integrated HPWH. These will be referred to from this point on as Unit A, Unit B, Unit C, Unit D, and Unit E, respectively. The testing took place between October 2010 and May 2011, and occurred in three rounds. Two HWPHs were tested at a time during each round of testing. Unit B and Unit C were tested during the first round, Unit A and Unit D during the second round, and Unit E in the final round.

Table 1. Tests Performed on Each HPWH, With the Air and Water Conditions for Each Test Shown

Test Name	Dry bulb (°C/°F)	RH	Inlet Water (°C/°F)	Tank Set Point (°C/°F)	Airflow	Operating Mode
1. Operating Mode Tests						
OM-67	20/67.5	50%	14/58	57/135	100%	All Factory Modes
OM-95	35/95	40%	14/58	57/135	100%	Hybrid Modes
OM-47	8/47	73%	14/58	57/135	100%	Hybrid Modes
2. Draw Profiles						
DP-1	20/67.5	50%	7/45	49/120	100%	Factory Default
DP-2	20/67.5	50%	7/45	49/120	100%	Factory Default
3. COP_{hp} Curve Development – Performance Mapping						
COP_{hp} -47	8/47	73%	2/35	57/135	100%	Compressor Only
COP_{hp} -57	14/57	61%	2/35	57/135	100%	Compressor Only
COP_{hp} -67	20/67.5	50%	2/35	57/135	100%	Compressor Only
COP_{hp} -77	25/77	40%	2/35	57/135	100%	Compressor Only
COP_{hp} -85	29.5/85	42%	2/35	57/135	100%	Compressor Only
COP_{hp} -95	35/95	40%	2/35	57/135	100%	Compressor Only
COP_{hp}-95 dry	35/95	20%	2/35	57/135	100%	Compressor Only
COP_{hp} -105	40.5/105	42%	2/35	57/135	100%	Compressor Only
COP_{hp} -105 dry	40.5/105	16%	2/35	57/135	100%	Compressor Only
4. Reduced Airflow						
AF-1/3	20/67.5	50%	2/35	57/135	66%	Compressor Only
AF-2/3	20/67.5	50%	2/35	57/135	33%	Compressor Only

During the second round of testing, OM-47 was not performed. During the third round of testing, the OM-95, OM-47, DP-3, COP_{hp} -105 dry, and AF-1/3 tests were excluded to shorten the testing schedule by removing low-value tests.

Operating Mode Tests

The operating mode tests were designed to discover the control strategies for each water heater in each mode of operation. Each test began with the water heaters full of water at the "Outlet Water" set point and the inlet air temperature at 20°C dry bulb. A draw was initiated and continued until the compressor turned on. 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, if possible, for that operating mode came on, or until 80% of the tank volume had been drawn. The units were then allowed to recover.

In addition to the 20°C dry bulb air condition, this procedure was followed in Hybrid mode only for air at 8°C dry bulb and 35°C dry bulb. This included the Hybrid mode for Unit A, the Hybrid and High Demand modes for Unit B, the Energy Saver and Normal modes for Unit C, on for Unit D, and Auto Mode for Unit E (Note: Units A, D, and E were not tested at the 8°C dry bulb air temperature because the results from this air condition provided little useful information during the first round of testing). Each mode of operation was tested at both the hottest water set point (60°C for Units A, B and D and ~57°C for Units C and E) and the standard 49°C set point.

Draw Profile Tests

Two draw profiles were used to challenge the water heaters with high volume draws and low volume draws over the course of several hours. The draw profiles, suggested by Ecotope, Inc., are based on NREL work (Hendron 2010), and a tabular representation of each profile can be found in Appendix A. Each test began with a full tank at the standard 49°C (120°F) set point.

Draw Profile 1 contained a "morning" segment and an "evening" segment. The morning segment contains four showers over the course of an hour to test the performance in high demand situations. The evening segment of Draw Profile 1 contained a range of flow rates and draw durations to simulate the variety of hot water draws that can occur, such as dishwashing and food preparation. After the morning draws were completed, the units were allowed to recover fully before starting the evening segment. Full recovery was deemed complete when all the heating elements, either the electric resistance elements and/or the heat pump, were turned off by the water heater's controller. Draw Profile 2 consisted of many short draws and was allowed to run uninterrupted. Depending on tank size and recovery rate, these draw profiles have the potential to deplete the hot water reserve, resulting in warm or even cold water being delivered to the users. For the results of these tests, "hot" water was defined as anything above 40.5°C (105°F).

The results from the Draw Profile tests were used to calculate system COP values for the HPWH running as a complete system. This means that if the HPWHs used back-up electric resistance heat, the COP value would reflect this. For the remainder of this report, the system COP will be referred to as COP_{sys}. The method used to calculate COP_{sys} values is defined in the following subsection.

The Draw Profile tests also provided an opportunity to measure the standby heat loss coefficient (UA). UA can be calculated anytime that the water heater is idle, neither heating the tank nor experiencing draws. The standby heat loss coefficient was calculated as:

$$UA = \frac{\left(T_{max} - T_{f,stby}\right) V_{st} \rho C_P}{\tau_{stby}\left(T_{t,stby} - T_{a,stby}\right)}$$

where T_{max} is the maximum mean tank temperature after the tank has fully recovered, $T_{f,stby}$ is the mean tank temperature at the end of the standby period, V_{st} is the measured volume of the storage tank, ρ is the density of stored hot water at the average of T_{max} and $T_{f,stby}$, C_P is the specific heat of the stored water at the average of T_{max} and $T_{f,stby}$, τ_{stby} is the elapsed time of the standby period, $T_{t,stby}$ is the average tank temperature over the entire standby period and $T_{a,stby}$ is the average ambient air temperature over the entire standby period.

COP$_{hp}$ Tests

The energy efficiency gained from a HPWH is due to its ability to transfer more heat from the air into water than the energy consumed by that transfer process. Thus, a series of tests were conducted to examine refrigerant system performance alone. To ensure the resistance heaters did not turn on, they were electrically disconnected for the units without a heat pump-only mode. The results from these tests were used to calculate a COP for the heat pump operating alone. The COP for the heat pump operating alone will be referred to as COP$_{hp}$ for the remainder of this report.

Unlike the other tests, the COP$_{hp}$ tests began with a tank full of cold water. Each tank was empty to start the day and the tanks were filled with 3°C (or colder) water. Once the water heaters were full of cold water, the units were turned on in their most efficient operating mode: Efficiency for Unit A, eHeat for Unit B, Energy Saver for Unit C, and Econ for Unit E. Unit D has only one operating mode, so this unit was turned on without selecting a mode. The test was deemed complete when the tank set point was achieved.

To run these tests using the heat pump only, Units A and C needed to be modified because the compressor is disabled when the water temperature is below 27°C in the case of Unit C and 14°C in the case of Unit A. Also, the electric resistance elements were disabled for Units C and D since both these units can use their heating elements in conjunction with the heat pump, even in their most efficient operating mode. The modifications needed to ensure compressor-only operation are discussed in more detail in the summary sections for each HPWH.

As mentioned previously, the results of these tests were used to calculate the COP$_{hp}$ for the operation of the heat pump alone across a wide range of air and water temperatures. The coefficient of performance is the measure of useful energy transferred to the water (output) divided by the input energy to the system (supplied work). The equation used to calculate COP is given below.

$$COP = \frac{Q_{thermal}}{W_{Input}} = \frac{m \cdot Cp \cdot (\Delta T)}{W_{Input}}$$

In this equation, m is the mass of water in the tank, Cp is the specific heat of water, and ΔT represents the difference in average tank temperature over a given time step, which, in this case, is 1 minute. Average tank temperature is calculated as the arithmetic mean of the six thermocouples mounted inside the tanks. The supplied work consists of the overall input energy to the unit, which includes the energy used by the heat pump, fan, electronic display, and circulation pump, if applicable. The heating capacity of the compressor, a useful quantity for modeling purposes, was also captured during this test. Heating capacity is defined as:

$$Heating\ Capacity = \frac{Q_{thermal}}{t}$$

where $Q_{thermal}$ is the thermal energy from the previous equation and t is the time step. The heating capacity for all units can be found in Appendix C.

The COP of the entire system, COP_{sys}, values were calculated for the draw profiles mentioned above. This calculation is different from the COP_{hp} calculations in that m is the mass of the volume drawn and is determined using the volumetric flow rate and ΔT is the difference between the outlet and inlet water temperatures during draws. The supplied work term also includes the energy used by the electric resistance elements.

NOTE 1: Standby losses are not inherently included in the thermal energy term of the COP_{sys} calculations because the inlet and outlet temperatures are used to calculate the thermal energy. This is in contrast to COP_{hp}, which uses the average temperature within the tank to calculate thermal energy, and therefore takes into account standby losses. In order to include the standby losses in the thermal energy term of the COP_{sys} calculations, the UA values calculated during the Draw Profile tests were used to determine the thermal loss associated with the tank. This loss was then added to the thermal energy term in the COP_{sys} equation.

NOTE 2: The performance of the heat pump depends on both temperature and humidity, so graphs showing the COP_{hp} curves reference the inlet air temperature as a wet bulb temperature (see Figure 10, Figure 16, Figure 22, Figure 28, and Figure 34).

NOTE 3: Any data for COP_{hp} presented in this report inherently includes standby losses. However, when COP_{hp} is used in future models, the curves will be modified to remove the standby losses using the UA values calculated during the Draw Profile tests.

Reduced Airflow Tests

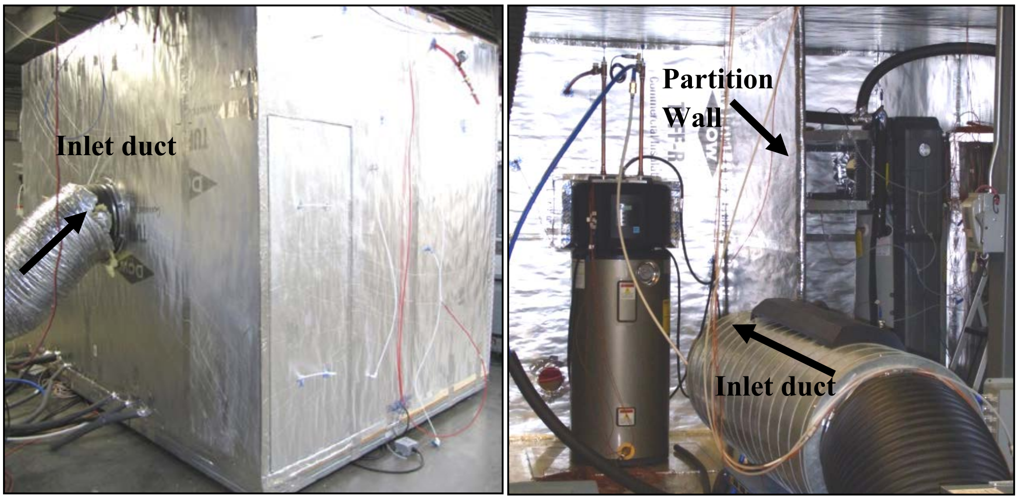
The setup for these tests was identical to the COP_{hp} tests described above, but the filter area was restricted for each water heater. Tape was used to block one-third and then two-thirds of the filter's surface area for these tests. These tests were designed to see the impact on performance if the filter was never cleaned or if something was obstructing the air intake area. COP_{hp} curves were calculated for these tests using the same method as described above for the COP_{hp} tests.

Laboratory Setup

This section describes the laboratory setup used to conduct the above test plan. The setup is divided into two sections: the air-side of the experiment and the water-side of the experiment. Real-time measurements taken on the two sides of the experiment were used to accurately control the air and water conditions at the inlet to the experiment and were used to determine the performance of each test article. Schematics for both setups can be found in Appendix B.

Test Plenum

Each test article was enclosed in an insulated air plenum. During the first round of testing, Units B and C were enclosed in the same test plenum that was physically partitioned (but not air sealed) to ensure that the operational cycle of one HPWH did not affect the operation of the other one. Units A and D were tested together during the second round of testing. The third round of testing was conducted on Unit D alone.



NREL/PIX 18678 and 18670, Credit: Kate Hudon

Figure 1. Test plenum during normal testing (left) and during installation (right)

An inlet duct was attached to the test plenum, creating a means to control the environment from which the heat pump drew air. At all times, the plenum's inlet airflow was greater than the total airflow used by the HPWHs, to allow excess conditioned air to exit the plenum via a bypass air duct. As a result, uniform ambient conditions were assured in the proximity of the tanks. When a heat pump was operating, its exhaust air was collected in an outlet plenum connected to an outlet duct. The outlet plenums were not connected to each other.

Air-Side Equipment

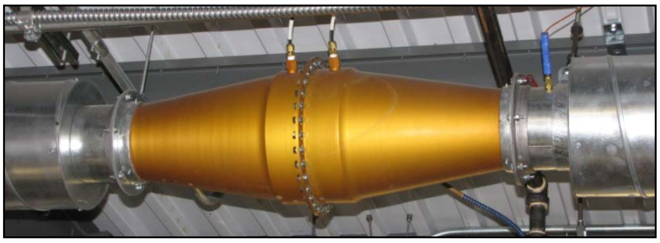
A schematic of the air conditioning equipment that was used during this project can be found in Appendix B, Figure 43. The conditions specified in the test plan require that accurately controlled conditioned air be supplied to and around the test article. Across the range of tests, the air within the test plenum needed to be heated, cooled, and/or humidified to achieve the desired inlet air conditions.

Moisture was added to the air via evaporation pads. Moisture addition was controlled by heaters located upstream of the evaporation pads. Once the required water content was attained, the air was either heated further by additional electric resistance heaters or cooled using a chiller and heat exchanger system. The temperature and humidity was measured in a duct directly upstream of the plenum inlet to ensure accurate inlet air conditions to the test articles.

NREL/PIX 18683, 18687, 18688, and 19464
Credit: Kate Hudon

Figure 2. Duct heaters used to control humidity (top left), heat exchanger to provide cooling (top right), evaporation pads (bottom left), and temperature and humidity measurement at inlet to plenum (bottom right)

Inlet airflow rate was measured using ASME standard flow nozzles located downstream of the evaporative pads. The inlet pressure was measured using four static pressure taps located in the test plenum. These pressure taps were physically averaged together prior to measurement. The temperature and humidity of the air exiting each of the test articles was measured in an outlet duct located directly downstream of the units. The outlet pressure was measured with static pressure taps located in each test article's outlet plenum. Each outlet duct was routed to a laminar flow element for accurate measurement of heat pump airflow rate. Boost fans were used to overcome the pressure drop of laboratory equipment in the exhaust airstreams, thus preventing the test articles from experiencing any performance-degrading backpressure.



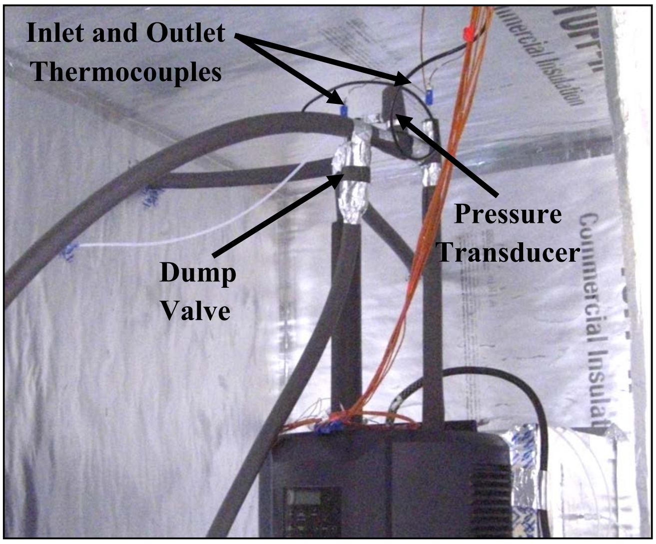
NREL/PIX 18679, Credit: Kate Hudon

Figure 3. Laminar flow element used to measure airflow rates out of HPWHs

Water-Side Equipment

A schematic for the water-side equipment can be found in Appendix B. For each test, a steady and well-controlled inlet water temperature was required to emulate a range of water main temperatures. A large holding tank was preconditioned prior to each test and maintained at the desired temperature using a heater or chiller with a heat exchanger. An icemaker was used to rapidly reach colder inlet water temperatures.

A water dump solenoid valve was actuated prior to the beginning of each draw to flush the inlet pipe with water at the desired "Inlet Water" set point temperature. The inlet water temperature and pressure was measured immediately upstream of the test article and the outlet water temperature and pressure was measured immediately downstream of the test article. Location of inlet and outlet thermocouples was based upon the DOE test specifications found in 10 CFR Part 430, Subpart B, Appendix E (DOE 1998). The inlet and outlet water pipes were insulated to limit heat transfer between the pipes and their surroundings.



NREL/PIX 18666, Credit: Kate Hudon

Figure 4. Inlet pressure transducer and thermocouple, outlet thermocouple, and dump solenoid valve on Unit B

A thermocouple tree consisting of six thermocouples was placed within each test article to measure stratification in the tank. Care was taken to position these thermocouples at the center of uniform volumes of water, which was often a challenge due to the non-uniform interior profile of some tanks. The thermocouple tree construction was also specified by the DOE test specification document (DOE 1998). These measurements were also necessary to calculate the performance of the test articles and to help understand their control logic.

Figure 5. Thermocouple tree prior to installation

The inlet and outlet water flow rates were measured using turbine flow meters. The only method to accurately measure condensate flow and condensate density from the heat pump is a coriolis flow meter. A coriolis meter was attached to the evaporator drain pan of each test article to measure condensate production. The temperature of the condensate flow was also measured.

NREL/PIX 18684 and 18686,
Credit: Kate Hudon

Figure 6. Inlet turbine flow meters (left) and coriolis flow meter for condensate (right)

For the tests having a prescribed water draw profile, an electronically controlled proportional valve was used. Draw profiles were preprogrammed and the turbine flow meter measurements at the test articles' outlets were monitored during draws to ensure the correct flow rates. Prior to testing, a correlation was established between the percentage opening in the value and the resulting flow rate for each HWPH. This correlation was used to write draw profile programs that were tailored for each HPWH. The water from the outlet line was directed towards a laboratory drain.

NREL/PIX 18685,
Credit: Kate Hudon

Figure 7. Outlet turbine flow meters, proportioning valves, and solenoid valves used to control outlet flow rate and draws

Test Article Summary

Five integrated HPWHs were tested: the A. O. Smith Voltex hybrid electric HPWH, the GE GeoSpring water heater, the Rheem Hybrid Electric water heater, the Stiebel Eltron Accelera 300 HPWH, and the Air Generate AirTap Integrated HPWH. Again, these will be referred to as Unit A, Unit B, Unit C, Unit D, and Unit E throughout the report. All five units are considered hybrid HPWHs because they all have back-up electric resistance elements that can heat the water like a traditional electric water heater. While all units are similar in design and operation, each system is unique. The characteristics of all units are summarized in Table 2.

Table 2. Summary of the physical characteristics of the HPWH units tested

	Nominal Capacity (Gallons)	Compressor Power (W)	Electric Element Sizes (kW)	Refrigerant	Condenser Type	Circulation Pump	Water Lines
Unit A	80	960	4.5 Upper 2.0 Lower	R-134a	Wrap-Around Tank	No	Side/ Horizontal
Unit B	50	700	4.5 Upper 4.5 Lower	R-134a	Wrap-Around Tank	No	Top/ Vertical
Unit C	50	1000	2.0 Upper 2.0 Lower	R-410a	Coaxial Heat Exchanger	Yes	Side/ Horizontal
Unit D	80	500	1.7 Upper	R-134a	Wrap-Around Tank	No	Side/ Horizontal
Unit E	66	800	4.0 Upper	R-410a	Immersed Coils	No	Side/ Horizontal

Units B and C have a rated capacity of 50 gallons, while the Units A and D have a rated capacity of 80 gallons and Unit E has a tank with a rated capacity of 66 gallons. Measured tank capacity was about 45.5 gallons for Units B and C, 75 gallons for Unit A, 80 gallons for Unit D and 63 gallons for Unit E. The compressors have slightly different power draws, with Unit D having the smallest compressor at 500 W and Unit C having the largest compressor at 1000 W. The combination of electric resistance elements also varies for each unit, with Unit B having two 4.5 kW elements, Unit C having two 2.0 kW elements, and Unit A having a 4.5 kW upper element and a 2.0 kW lower element. Units D and E have only a single back-up resistance heater, but Unit E has a 4.0 kW heater whereas Unit D has a small 1.7 kW heater. Units A, B and D use R-134a refrigerant and a wrap-around style of condenser. In contrast, Unit C uses R-410a refrigerant and pumps water from the bottom of its tank and through a coaxial heat exchanger that serves as its condenser. Unit E also uses R-410a refrigerant but its condenser is an immersed coil that sits inside the tank near the bottom. The inlet and outlet water lines are vertical and come through the top of the tank for Unit B, whereas all other units have horizontal inlet and outlet water lines that are found on the side of each tank.

The performance characteristics and control logic of each of these units also differ and will be discussed in more detail in the following section.

Test Results

The results for each HPWH are described in the following sections. The specific test results are summarized and overall impressions are given for each test article. A list of suggested improvements is also provided where opportunity for improving performance was uncovered. The suggestions given are based on our understanding of expectations that will be placed on a HPWH in an American home. By incorporating all the best features across the five brands of HPWHs, each one individually could be improved.

Uncertainty Analysis

An uncertainty analysis was performed for all major results presented in this paper. Standard error propagation was performed and the associated uncertainty for each measurement is presented alongside the major result (Taylor 1997). The error analysis presented takes into account sensor accuracy as provided by the manufacturers. The random error component could not be characterized since each test was only completed once.

Unit A HPWH Summary

Overall Impressions and Observations

Unit A has a large storage tank and control logic that turns on the heat pump after small draws and is able to deliver hot outlet water for all tests performed. It has an efficient heat pump that can quickly heat the tank of water, even with an 80-gallon tank. The logic controlling the electric resistance elements in Hybrid mode is intended to quickly provide hot water when demand is high, but the majority of the heating load is provided by the heat pump. The engineers also chose a smaller lower resistance element that only operates in Electric Only mode to encourage the use of the Hybrid mode. The smaller lower element means that the Electric Only mode is equal to or slower at heating the full tank than Hybrid mode. Overall, this unit succeeds in providing hot water for all scenarios tested and can maintain a high level of performance, even at low ambient temperatures.

NREL/PIX 18675, 18673, and 18674, Credit: Kate Hudon

Figure 8. Unit A 80 gallon HPWH installed in test plenum (left). A close-up of the compressor and refrigerant system in Unit A (upper right) and a side view of the evaporator coils and heat exchanger (lower right).

Installation and Usability Considerations

Unit A’s inlet and outlet water lines are located on the side of the tank. The 80 gallon unit that was tested is nearly 7 ft tall. This could limit the possible installation locations in a home, especially in a retrofit situation. The 60 gallon version of Unit A is 5 ft 7 in. tall and may be a better choice if space is limited. Also, the 80 gallon unit tested requires an airflow rate of about 500 cfm. This means that the installation requirement for a location with unrestricted airflow is very important for Unit A. The air enters the unit from the left (when viewed from the front), is pulled across the evaporator coils located in the middle of the heat pump, and exits from the right of the unit. The air filter slides into the front of the top cover and is secured with a screw. Currently, Unit A is not available through a major retailer, but can be purchased through plumbing suppliers.

The user interface displays information about the current set point, the heating elements currently being used, the current mode and ways to change the mode and set point, but the touch screen is not as responsive as it should be. Buttons may need to be pressed a few times before it responds. The operating mode controls are accessible and clearly labeled, and changing the set point is also obvious. There are three operating modes available: Efficiency, Hybrid, and Electric. There is also a Vacation mode that reduces the temperature set point to approximately 15°C. Changes made to operating mode take place almost immediately. When the heat pump is turned on, from off or as a result of a change in operating mode, the fan will turn on immediately and the compressor will turn on approximately 1 minute after the fan.

Qualitative Test Results and Observations

The descriptions below explain the results of the tests run on Unit A HPWH and the observations made during testing.

Operating Mode Tests

Unit A has two thermistors affixed to the exterior of the tank (under the insulation layer) that are used to control the heat pump and electric elements. The thermistors are located at the same height as the backup resistance elements. The following equation, which was provided by the manufacturer, shows the average tank temperature estimate that is used to control this unit:

$$T_{tank,mfr} = \left(3 * T_{upper} + T_{lower}\right)/4$$

In this equation, T_{upper} is the temperature measured by the upper thermistor and T_{lower} is the temperature measured by the lower thermistor. The upper thermistor is located near the upper heating element and the lower thermistor is located near the lower heating element.

This quantity is monitored to dictate when heating is required. None of the heat sources—the heat pump, the upper electric element, or the lower element—can operate concurrently with another. Also, if the tank temperature is below 14°C upon initial startup, the heat pump will not run and the upper heating element will turn on instead.

Operation Modes and description:

1. <u>Efficiency Mode:</u> The heat pump turns on when $T_{tank,mfr}$ drops 5°C below the set point temperature and will run until $T_{tank,mfr}$ is equal to the set point. This mode of operation uses the heat pump exclusively unless the air temperature is outside the operating bounds, 7°C to 43°C, as defined by the manufacturer, or $T_{tank,mfr}$ falls below 14°C. If either of these conditions occur, the upper heating element turns on until T_{upper} reaches set point. The heat pump will then be used to finish the heating cycle, which is concluded when $T_{tank,mfr}$ equals the set point temperature.

2. Hybrid Mode: The heat pump will turn on when a 5°C drop in $T_{tank.mfr}$ is detected and the upper heating element will turn on in place of the heat pump when $T_{tank.mfr}$ has dropped by 10°C. The upper element will turn off when T_{upper} is at set point and revert to the heat pump to finish the heating cycle.

3. Electric Only Mode: Will only use electric resistance heating elements to heat the tank. A small drop in $T_{tank,mfr}$ (2°C) will cause the upper heating element to turn on. The upper element will remain on until T_{upper} is at set point. The lower element will then turn on to heat the rest of the tank. Because the lower heating element has a small heating capacity (2kW), this mode has no benefit over the Hybrid mode in either recovery time or efficiency. This mode should only be used if the heat pump is not performing correctly.

NOTE: For most air conditions, the compressor provides more heat input to the tank of water than the lower resistance element. In the worst case scenario, they provide about equal heat input. According to the engineers at Unit A's manufacturer, they chose the size of the lower element for this exact reason. They did not want the electric resistance mode to have a performance advantage over the Hybrid mode. This should ensure that Hybrid mode (or Efficiency mode) is used exclusively by homeowners.

Draw Profile Tests

Draw Profile 1 was tested in two parts. During the "morning" segment of Draw Profile 1, four showers are simulated over the course of a little more than an hour. Unit A was able to maintain an outlet temperature of 49°C during all four showers, with the only decrease in outlet temperature occurring at the very end of the fourth shower. This is well above the criteria for "hot" water (40.5°C). The compressor turned on after the first draw and remained on for the rest of the morning segment until $T_{tank,mfr}$ was equal to the set point temperature. The evening draws were also completed with no measurable dip in outlet temperature. The compressor came on about halfway through the evening portion and remained on until set point was achieved after the profile finished. Neither segment of Draw Profile 1 triggered the operation of the upper resistance element.

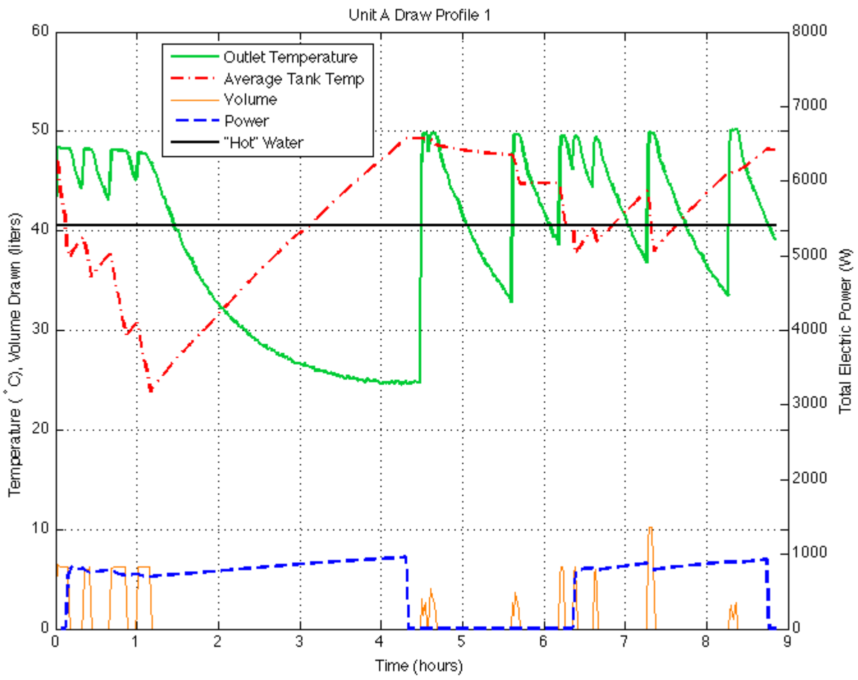


Figure 9. Draw Profile 1 for Unit A

Draw Profile 2 consisted of many small draws over a 6-hour period. Unit A performed well for this low-demand situation. The compressor turned on to reheat the tank about 4 hours into the 6-hour profile.

COP_{hp} Tests

The results of the COP_{hp} tests are plotted below in Figure 10. As expected, COP_{hp} increases as the inlet air temperatures increases and the COP_{hp} decreases as the water temperature in the tank increases. All tests were run in Efficiency mode to ensure that only the compressor was used to the heat the tank. Even at the lowest air temperatures, Unit A did not use its resistance elements. While COP_{hp} was lower at the colder air temperatures, there was not a dramatic decrease in COP_{hp} at the lowest air temperatures that would suggest there was icing on the evaporator coils.

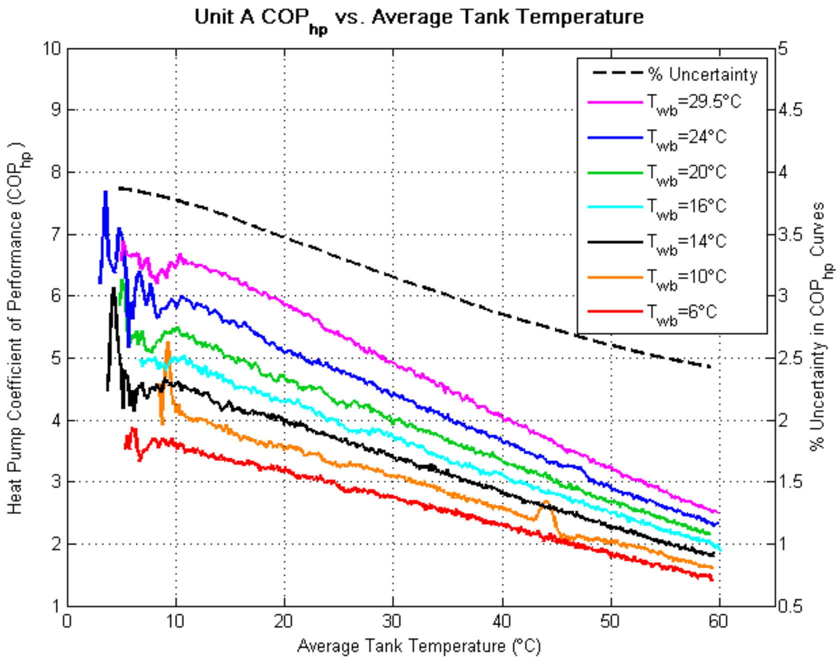


Figure 10. COP_{hp} traces for Unit A

The two warmest COP_{hp} tests were repeated with the same inlet dry bulb temperature for high and low relative humidity. Figure 11 shows this comparison for the inlet dry bulb condition at 35°C with the relative humidity at 40% and 19%. The corresponding wet bulb temperatures for these conditions are 24°C and 17°C, respectively.

The results show that the performance improvements were not significant for the COP_{hp} test run at the higher inlet wet bulb temperature. For the lower tank temperatures, a small increase in COP_{hp} can be seen. However, as the average tank temperatures increases, the performance difference becomes insignificant. The tank recovery time is shown in Figure 12. This shows that the lower humidity reduced the recovery rate from 10.5°C/hr to 10.4°C/hr. These results show that humidity has a small, but not significant, impact on the performance of this unit.

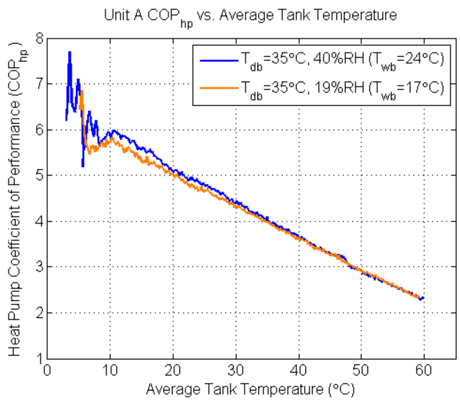


Figure 11. Effect of humidity on COP_{hp} for Unit A

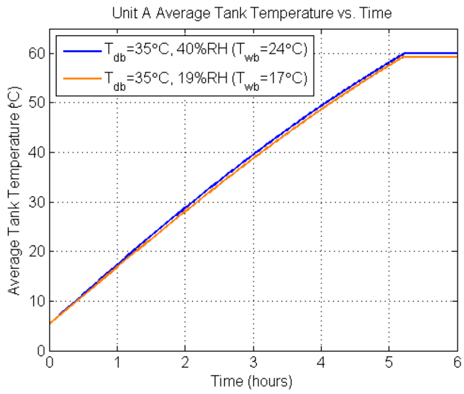


Figure 12. Effect of humidity on recovery time for Unit A

NOTE: To prevent situations where icing is more likely, the compressor will not run if the water in the tank is below 14°C. In order to run the COP_{hp} tests beginning with 3°C water temperatures, the thermistors fastened to the outside of the tank were moved so that they would sense the air temperature, rather than the water temperature. At the lowest air temperature tested, 8°C, the thermistors were wrapped in insulation and heated slightly to keep the compressor running. When tank set point was reached, the HWPH had to be manually shut off since these thermistors were also used to measure tank temperature and turn off power when set point is achieved. The thermocouple tree installed inside the tank for testing purposes was used to monitor when set point was achieved.

Reduced Airflow Tests

The results of the reduced airflow tests are shown in Figure 13. The results of the one-third airflow blockage test show an insignificant decrease in performance (<1% reduction in COP_{hp}). The results of the two-thirds airflow blockage test show a slight decrease in performance, ranging from ~6% to ~2 % over the course of the heating cycle.

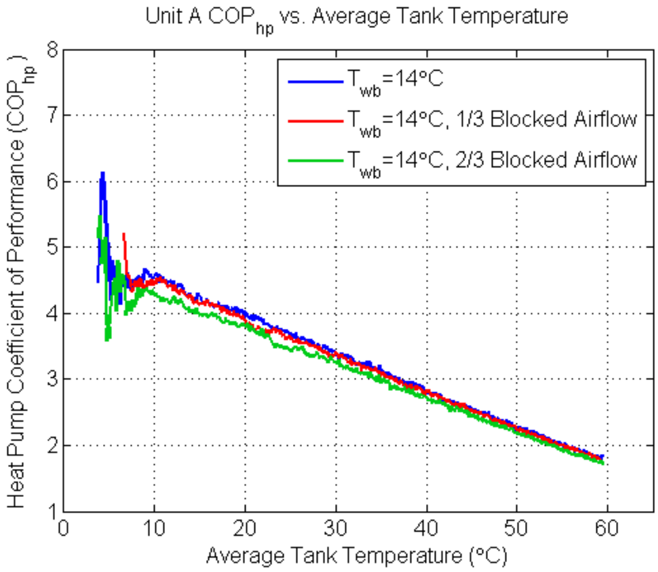


Figure 13. Heat pump COP_{hp} traces for Unit A HPWH with reduced airflow

System Drawbacks

Below is a list of system drawbacks that could be improved to enhance the capabilities of Unit A:

1. **The 80 gallon unit is very tall.** The large tank capacity has many benefits from a performance perspective, but its physical size may limit the homes in which it can be installed. The 60 gallon unit is smaller and so should fit in more homes, but there will likely be differences in hot water availability under high demand.

2. **Higher airflow required.** Unit A requires about 500 cfm of continuous airflow when the heat pump is operating. The installed location of this unit will need to accommodate this large airflow. Also, 500 cfm of cold air will likely be noticeable to the homeowners and could require ducting in some climates to prevent discomfort in the house during the winter months.

3. **Control panel touch screen is not sensitive enough.** The touch screen on the control panel is not very responsive. We found that we often had to touch a button multiple times before the command was received. However, the layout of the control panel is simple and the icons used are intuitive.

Unit B HPWH Summary

Overall Impressions and Observations

Unit B will use its heat pump to heat water the majority of the time, but two large electric resistance backup elements will turn on when faster recovery is needed. The compressor has a smaller capacity than most of the other units tested but it consistently operates across a wide range of conditions. The electric resistance elements were the largest of the five units in terms of combined power output, which allows Unit B to heat a full tank of water quickly when demand is high. The eHeat mode uses only the heat pump for maximum efficiency while the Hybrid and High Demand modes use a combination of heat pump and resistance elements to meet demand, which can provide the user with faster recovery times in high demand situations. Unit B can be operated with minimal energy demand for energy-conscious users but also provides a higher energy-use mode to meet high water heating demands.

NREL/PIX 18671, 18664, and 18665, Credit: Kate Hudon

Figure 14. Unit B in the test plenum (left) and the instrumented heat pump components (right)

Installation and Usability Considerations

Installation of Unit B in our lab space was straightforward, without issue. The inlet and outlet water lines come directly out of the top of the unit, like most traditional gas or electric water heaters. The air filter lifts up from the top of the unit, and can easily be accessed for cleaning. The top cover can be removed without disturbing the water lines or power cable, providing access to the heat pump components for maintenance or repair. The unit is presently available for purchase through Lowe's.

The control interface on this unit consists of a LCD screen with a key pad and buttons used to change settings. The user must navigate through multiple menus to change the set point temperature or select an operating mode. Unit B can be operated in four modes: eHeat, Hybrid, High-Demand, and Electric Only. If modes are switched while the compressor or heating elements are running, the change takes place immediately. Initial start-up in eHeat or Hybrid mode results in the fan turning on immediately followed by the compressor, 2–3 minutes later.

The air enters the heat pump from the neck and sides and is pulled across the evaporator coils to the exit at the back of the unit using two variable-speed, direct-current fans. To measure the speed of the variable speed fans, an optical tachometer was installed on one of the fans. We also measured the speed of the second fan to ensure that they operate identically, which confirmed the information provided by the engineers from the manufacturer. The variable speed fans ramp up to compensate in times of reduced air flow and their speed also varied in response to changes in inlet air conditions.

Qualitative Test Results and Observations

The descriptions below explain the results of the tests run on Unit B and the observations made during testing.

Operating Mode Tests

Unit B does not allow either of the two electric resistance elements to operate simultaneously with the other, nor with the heat pump. Below is a description of the control logic that was determined during the operating mode tests. According to the manufacturer, a thermistor located near the upper heating element is used as input to the unit's controller.

Operation Modes and Description:

1. eHeat Mode: The heat pump will turn on once a small temperature drop (0.5°C) is detected by the thermistor. This mode uses the heat pump exclusively unless the air temperature is outside the operating bounds, defined by the manufacturer as 7°C to 49°C. The heating elements will turn on if icing on the evaporator coils is imminent. This mode is very efficient, but tank recovery is slow due to the smaller heating capacity of the compressor.

2. Hybrid Mode: Similar to eHeat mode, the heat pump will turn on once a small drop in temperature is measured by the thermistor. A more significant drop in temperature (10°C) will cause a heating element to turn on. The lower heating element turns on first for moderately large draws and the upper element turns on first for very large draws. If the lower element turns on first, it will heat the tank to the set point temperature without ever using the upper element. If the upper element turns on first, it will remain on until the thermistor at the top of tank reads a temperature 3°C below set point temperature. The lower element will then turn on to heat the rest of the tank to the set point temperature. During our test, once an electric element has turned on, the remainder of the heating cycle will be accomplished with electric heat. However, according to the manufacturer, a

sequence of smaller draws can trigger the use of the upper element but then revert to the heat pump after the top of the tank is at set point. This behavior was not seen during our tests.

3. High Demand Mode: This mode is very similar to Hybrid mode, but the electric elements will turn on sooner than in Hybrid mode, when the temperature at the thermistor drops 3°C.

4. Electric Only Mode: The upper element will turn on after a minimal drop in temperature (~0.5°C) at the thermistor and will heat until the top of the tank is 3°C below the set point. The lower element will then turn on to heat the rest of the tank. The lower element will turn off when the thermistor near the top of the tank reads the set point temperature. This mode offers a quick recovery to the set point temperature, but is the least efficient of the modes due to its sole reliance on electric resistance elements.

Draw Profile Tests

Draw Profile 1 was implemented in two segments: the morning segment and the evening segment. The results of this test are shown in Figure 15. During the first part, which simulated four consecutive morning showers, Unit B was able to maintain 'hot' water (>40.5°C) for the first two showers but the outlet temperature dropped below that temperature during the third shower. While supplying the second set of draws, which simulated evening use, the test article was able to maintain 'hot' outlet temperature during all but one draw. The evening draw profile consumed a lower total volume of hot water over a longer period of time, allowing the water heater to keep up with demand better than in the morning draw profile. During both portions of Draw Profile 1, the compressor came on first, and when demand was too great, electric resistance elements took over for the remainder of the heating cycle. The upper element came on first, until the top of the tank was slightly below the set point temperature, then the lower element turned on to bring the entire tank to the set point temperature. The resulting efficiency was much lower than would be accomplished by running the heat pump alone.

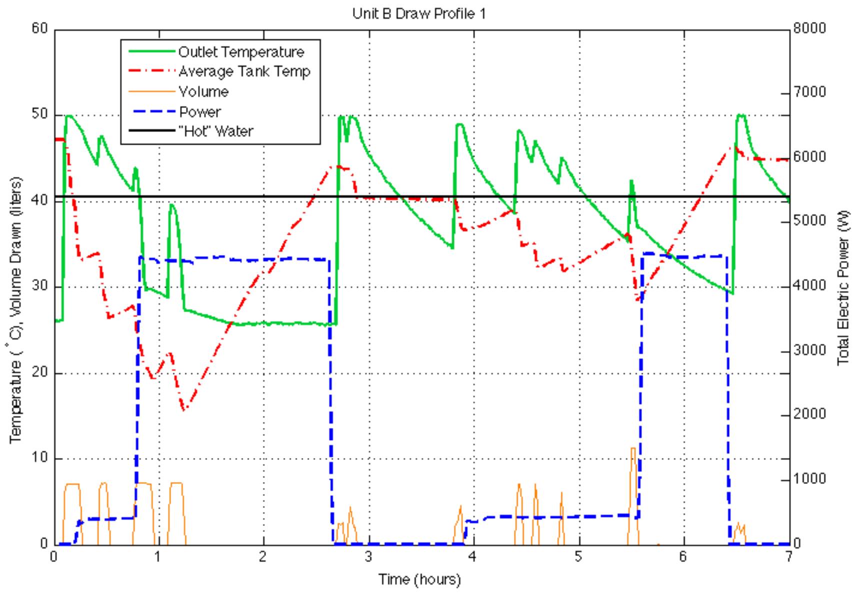


Figure 15. Draw Profile 1 for Unit B

Draw Profile 2 consisted of many short draws spaced over a 6-hour period. The results of this test show that Unit B performed well under this low-demand condition since only the compressor was needed to maintain set point temperature.

COP_{hp} Tests

Results of the COP_{hp} tests are plotted below in Figure 16. As expected, COP_{hp} increases as the inlet air temperatures rise and the COP_{hp} decreases as the water temperature in the tank increases. All tests were run in the eHeat operating mode to achieve compressor-only operation. At the lowest inlet air temperatures, operation switched from the heat pump to the upper element while the average tank temperature was still colder. Under normal operation, the heat pump would not turn back during the heating cycle, so power was manually cycled. This eventually allowed the heat pump to operate continuously to complete the heating cycle. Icing may have been the reason that the upper element was called for.

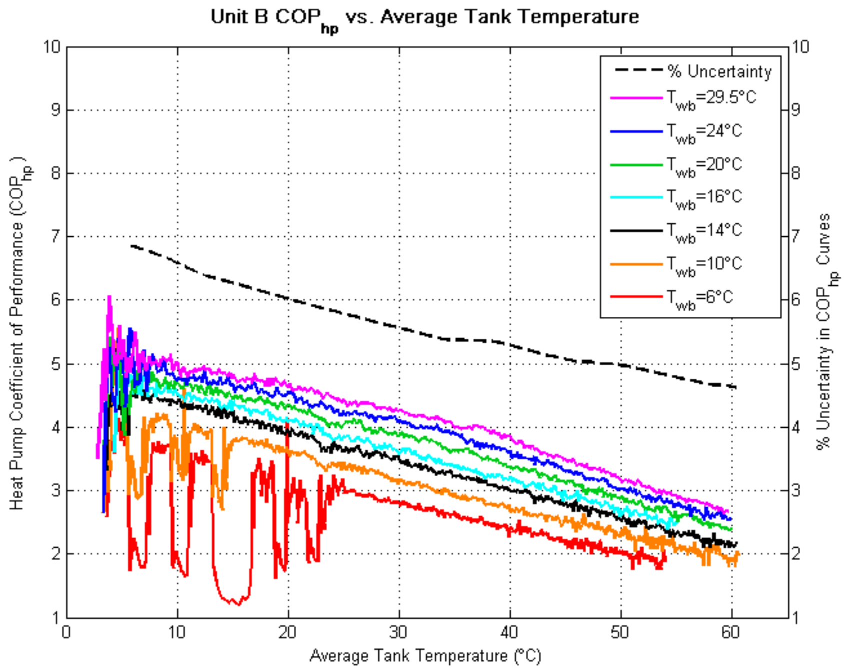


Figure 16. COP_{hp} traces for Unit B

The two warmest COP_{hp} tests were repeated with the same inlet dry bulb temperature for high and low relative humidity. It was expected that the inlet conditions with the higher humidity (i.e. higher wet bulb temperatures) would perform better than the lower humidity conditions. Figure 17 shows this comparison for the inlet dry bulb condition at 35°C with the relative humidity at 40% and 19%. The corresponding wet bulb temperatures for these conditions are 24°C and 17°C, respectively. The results show that the performance improvements were not significant for the COP_{hp} test run at the higher inlet wet bulb temperature. On average, the increase in COP_{hp} was ~1%. The tank recovery time for two humidity levels is shown in Figure 18. The lower humidity slowed the recovery rate from 9.6°C/hr to 9.4°C/hr. These results show that humidity has a small, but not insignificant, impact on the performance of this unit.

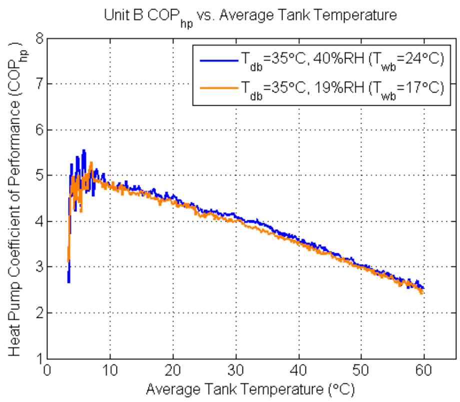


Figure 17. Effect of humidity on COP_{hp} for Unit B

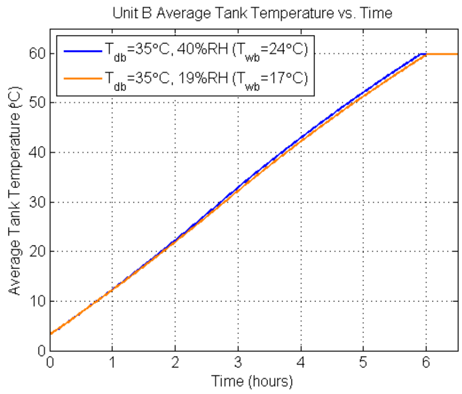


Figure 18. Effect of humidity on recovery time for Unit B

Reduced Airflow Tests

Blocking the airflow path by one-third resulted in a minor system performance drop, and an additional small performance reduction resulted from the two-thirds airflow blockage. However, in neither case was performance impacted significantly; this can be attributed to the variable speed fans. These results are shows in Figure 19. For the case of the one-third airflow blockage, the fan speed was seen to be greater than the nominal case at the higher water temperatures only. In the case of one-third blockage, the fan power reached a maximum of 23 W, the same maximum of the unblocked case, but it remained at this maximum value for 1-½ hour longer before the fan speed decreased as the tank temperature approached set point. In contrast, for the two-thirds airflow reduction, the fans immediately went to their maximum speed, corresponding to 28 W, and remained there for the entire test in an apparent effort to counteract the airflow restriction.

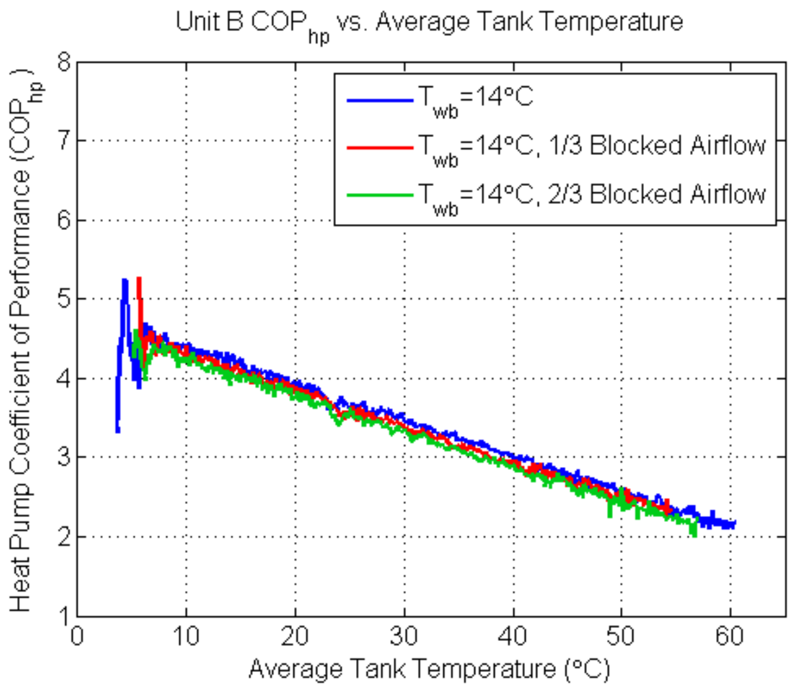


Figure 19. COP_{hp} traces for Unit B with reduced airflow

System Drawbacks

Below is a list of system drawbacks that could be improved upon to enhance the capabilities of Unit B:

1. **Slow recovery time.** The recovery time for this unit is very long if the heat pump alone is used. This could be an issue for homeowners who demand equivalent performance and improved efficiency when switching to HPWH technology. A smaller upper electric resistance element that could be used in conjunction with the compressor would help improve recovery time while still taking advantage of the efficiency of the heat pump. A larger tank would not improve recovery time but would provide a larger buffer. Even in situation of high demand, a large tank could consistently supply hot water without needing to revert to the electric elements.

2. **Control algorithm did not switch back to the heat pump if electric resistance elements are called for**. In Hybrid and High-Demand modes, if the electric resistance elements are used because of a high-demand situation, the compressor did not turn on again until the reheat cycle is complete. According to the manufacturer, the heat pump should turn on after the upper element in times of moderate to high demand, but that behavior was not reproduced in the laboratory. However, the manufacturer regularly sees this behavior in the numerous field installations they monitor. The control logic that allows the heat pump to turn back on may need to be revised so that it is easier to achieve, as opposed to the logic that uses the upper element and then the lower element when demand is high.

3. **User interface is not user-friendly.** A simple task like changing the operating mode requires navigating through multiple screens. A more straightforward display may encourage people to maximize the efficiency of the unit by changing the temperature setting and operating mode to meet their changing needs.

Unit C HPWH Summary

Overall Impressions and Observations

Unit C is the most complicated of all the units tested, in both physical design and control logic. To transfer heat from the heat pump to the water, Unit C pumps water from the bottom of the tank, through a coaxial heat exchanger/condenser at the top of the unit, and back into the top of the tank. This requires a pump that consumes 70 W any time the heat pump is running. The pump also thoroughly mixes the tank, which can lead to a decrease in outlet temperature since the relatively cold inlet water is quickly mixed with the hot water in the tank. Unit C did not operate its compressor over the range of operating temperatures stated in its manual; this behavior is described in more detail below. However, when in the optimal air conditions, the high capacity compressor can quickly heat a full tank of water. This unit also has two smaller (2 kW each) electric resistance elements, one of which can operate concurrently with the heat pump. This allows for faster and more efficient tank recovery than if a larger electric element was used alone. Unit C performed very well in a narrow range of conditions but suffered performance impacts outside that range.

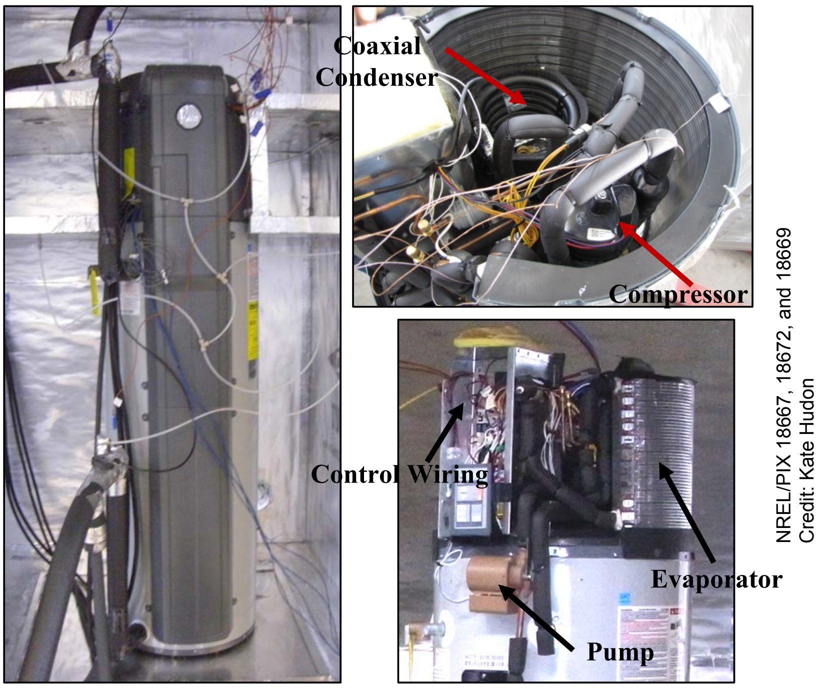


Figure 20. Unit C in the test plenum (left), the compressor and coaxial heat exchanger (top right), and the water circulation pump, evaporator, and control wiring (bottom right)

Installation and Usability Considerations

The inlet and outlet water lines are located on the side of the tank. The air filter resides on top of the unit and is easily accessible for the homeowner. Access to the heat pump components for maintenance and repair can be achieved by disassembling the heat pump casing.

The air enters this unit from the top and is pushed across evaporator coils that encircle about two-thirds of the area around the heat pump. A minimum distance between the air inlet and the ceiling is specified by the manufacturer, and the location of the water heater must be considered to ensure installation requirements are met. This unit can currently be purchased at Home Depot.

The user interface is straightforward and user-friendly. This interface is used to make changes to the set point temperature and to select an operating mode. This unit can be operated in three modes: Energy Saver, Normal, and Electric Only. The interface provides a set point gradient from Hot to Normal to Vacation, without providing actual temperature of each set point. The homeowner must reference the manual to learn what setting corresponds to what temperature. If the compressor is turned on, there is a 20-minute delay before the compressor and fan turn on. This occurs both during initial start-up and if the user switches to Energy Saver mode from Electric-Only mode. In Electric-Only mode, the resistance heaters turn on immediately.

Qualitative Test Results and Observations

The descriptions below explain the results of the tests run on Unit C HPWH and provide observations made during testing.

Operating Mode Tests

The heat pump and upper heating element in this unit can operate concurrently. Both heating elements can also operate at the same time. A thermistor located near the lower heating element is used to trigger the operation of the heat pump and/or the electric resistance elements. A second thermistor located near the upper heating element determines when the heat pump or heating elements should be turned off. If the tank is filled with water below 27°C at initial start-up, the heat pump will not run and the upper resistance element will be used until the temperature exceeds 27°C. The heat pump will then turn on, if allowed by the operating mode. This information was provided by the manufacturer and confirmed during testing.

Operation Modes and Description:

1. <u>Energy Saver Mode:</u> The heat pump turns on when the thermistor located near the lower heating element reads a temperature around 22°C. The heat pump operates exclusively if the water temperature set point is 52°C or below, unless the air temperature is outside of the manufacturer-stated operating bounds (4°C and 49°C). When the set point is at its highest (58°C), the heat pump and upper element are used primarily. The use of the heat pump alone versus the use of the heat pump and upper element appears to be tied to the set point temperature, rather than draw size. Also, other than times when the air temperature was outside of acceptable bounds, there does not appear to be a scenario in Energy Saver mode that cause the two electric elements to operate alone, without the heat pump.

    - Even though the user manual states that the heat pump will operate in air temperatures between 4°C and 49°C, we did not see continuous operation of the heat pump for dry bulb temperatures below 14°C or above 35°C. For air temperatures below 14°C, ice built up on the evaporator coils, as indicated by three surface mounted thermcouples that were installed on the coils at the inlet, middle, and exit of the evaporator for the purposes of testing. This caused the heat pump to cycle on and off three times before switching to electric resistance heat for the remainder of the heating cycle. Above 35°C, the heat pump cycled on once before switching to the heating elements.

- It should also be noted that the upper element turns on at the very end of the heating cycle for the higher set points. (See Anomalies section below for further discussion.)

2. Normal Mode: This mode is very similar to the Energy Saver mode. For a 49°C tank set point, the heat pump will turn on alone, except at the very end of the reheat cycle when the upper heating element will also be used. For the highest set point (58°C), the heat pump and upper electric element turn on. The temperature trigger for the heat pump is the same as in Energy Saver mode. There is no apparent advantage to this operating mode when compared to the Energy Saver mode.

3. Electric-Only Mode: Both heating elements will turn on when the thermistor temperature drops to 20°C but the lower element turns on first, after a small drop in temperature (~0.5°C) is detected by the lower thermistor. The upper element will turn off when the top of the tank has reached set point and the lower element will remain on to finish heating the lower half of the tank.

Draw Profile Tests

Draw Profile 1 was tested in two segments, the morning segment and evening segment. During the morning segment, which simulated four consecutive morning showers, Unit C was able to maintain acceptably hot outlet water (>40.5°C) for the first shower but the outlet temperature started to drop by the beginning of the second shower. The outlet water temperature dropped quickly because the circulation pump turns on with the compressor and mixes the cold water from the bottom of the tank with the hot water at the top of the tank. During this portion of the draw profile, the heat pump cycled on and off three times, alternating between the heat pump and both electric resistance elements, before the elements remained on for the remainder of the heating cycle.

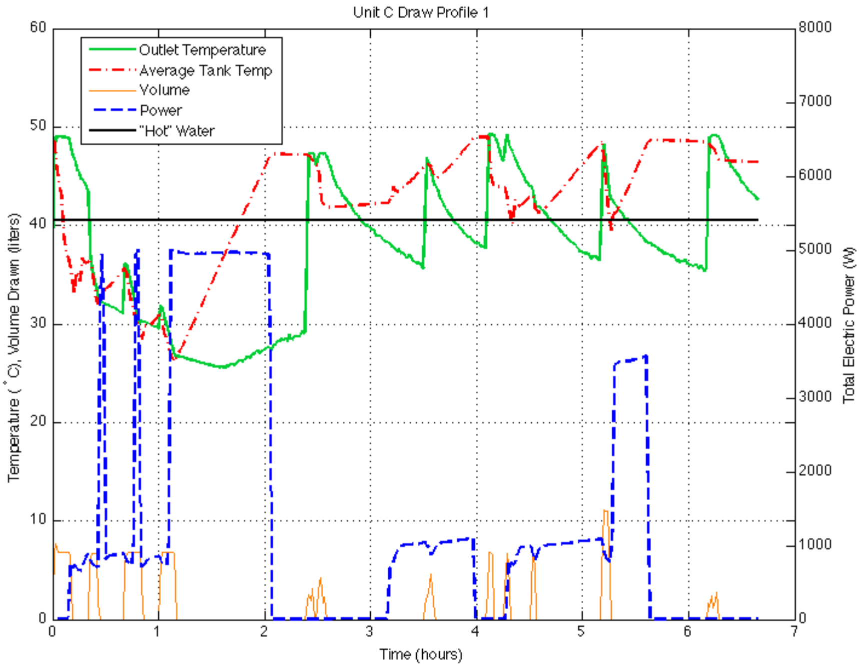


Figure 21. Draw Profile 1 for Unit C

During the second part of Draw Profile 1, which simulated evening use, Unit C was able to maintain hot outlet temperature during all draws. The compressor turned on twice during this profile, and the upper element assisted the compressor during a portion of the test. The combined use of the heat pump and electric resistance elements during Draw Profile 1 resulted in lower energy efficiency compared to running the heat pump alone.

Draw Profile 2 consisted of many small draws over a 6-hour period. Unit C performed well under this low-demand situation since only the compressor was needed to maintain set point temperature.

COP_{hp} Tests

The results of the COP_{hp} tests are plotted below in Figure 22. As expected, COP_{hp} increases as the inlet air temperatures rise and the COP_{hp} decreases as the water temperature in the tank increases. For inlet dry bulb temperatures ranging from 25°C to 35°C, the heat pump heated the water quickly and efficiently. For air temperatures below 25°C (16°C wet bulb), icing occurred on the evaporator coils during a portion of the heating cycle, resulting in compressor cycling. For the COP_{hp} tests at these cooler inlet air conditions, the power was reset after the compressor cycled three times to force heat pump operation until the set point was reached. For the case of 20°C inlet air, the compressor cycled at the lower water temperatures but remained on once the average tank temperature reached ~24°C. Below 20°C dry bulb (14°C wet bulb), the heat pump was never able to achieve continuous operation.

For COP_{hp} tests at air temperatures at and above 38°C, the compressor cycled on and off once before switching to both electric elements but did not turn on again. This was due to a fault that occurs when the temperature difference across the compressor is less than 20°C. This fault prevented the compressor from running at both high and low humidity for dry bulb temperatures above 35°C. It is unclear what this control feature is trying to prevent.

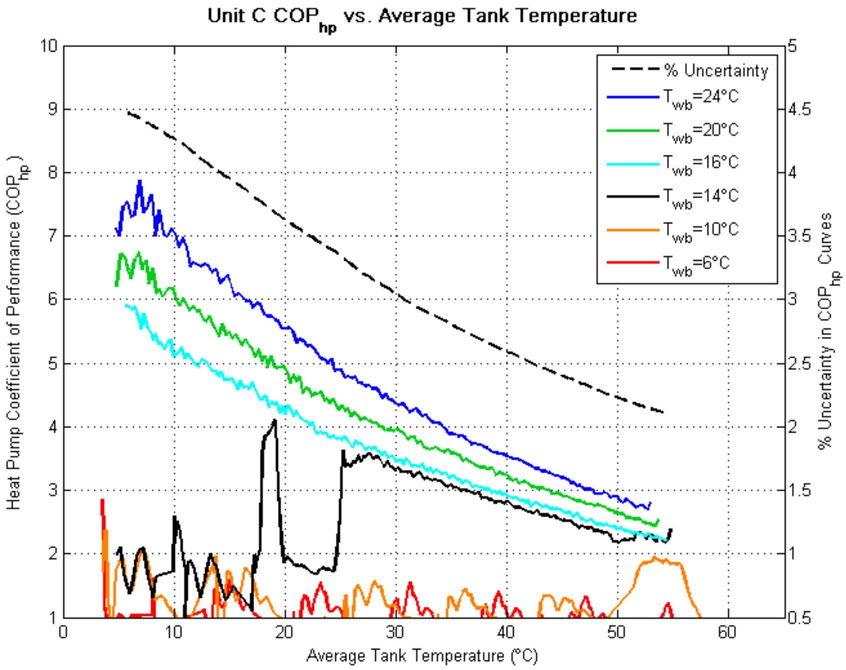


Figure 22. COP_{hp} traces for Unit C

The COP_{hp} test run at the highest dry bulb temperature was repeated with a lower relative humidity to determine the impact of humidity on performance. Figure 23 shows this comparison for the inlet dry bulb condition at 35°C with the relative humidity at 40% and 19%. The corresponding wet bulb temperatures for these conditions are 24°C and 17°C, respectively.

The COP_{hp} dropped by ~20% at the lower humidity case, showing that the performance of Unit C is sensitive to the humidity of the ambient air around it. The tank recovery time is shown in Figure 24. This shows that the higher humidity increased recovery rate from 14.1°C/hr to 17.8°C/hr relative to the lower humidity case at the same dry bulb temperature.

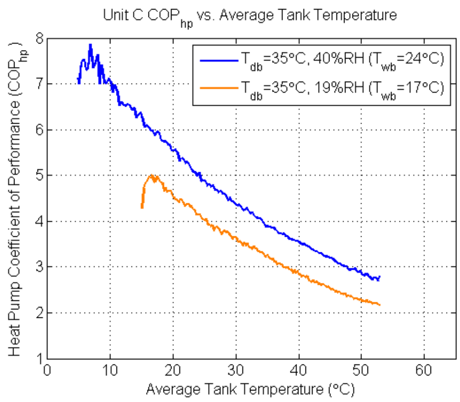


Figure 23. Effect of humidity on COP$_{hp}$ for Unit C

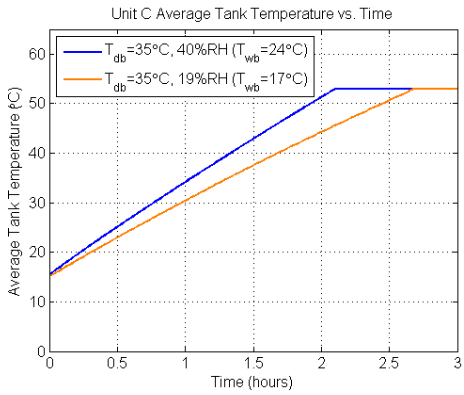


Figure 24. Effect of humidity on recovery time for Unit C

NOTE 1: Because of control logic restrictions, when initially turned on, the compressor does not turn on for water temperatures lower than 27°C. In order to perform the COP$_{hp}$ tests with 3°C starting water temperatures, we added a circuit containing a potentiometer in parallel with the lower thermistor. Using a manual switch, we could provide the control board with the actual water temperature or a false, warmer temperature. This successfully allowed the compressor to run for the coldest water temperatures. However, icing occurs more often on the evaporator when the water was cold (<27°C), which explains why that control logic is built in.

NOTE 2: Unit C regularly uses its electric resistance elements when in its most efficient mode. Manual switches were installed on both elements that could be used to disable their use. These switches were only used during the COP$_{hp}$ tests to ensure that only the compressor was running.

NOTE 3: To determine why the compressor was not operating under various conditions, we looked at the Fault Indicator Light, which is a red LED located on the circuit board (behind the control panel). This light will blink a prescribed number of times to indicate the reason for a compressor fault. The LED is not visible unless a hole is drilled in the plastic housing. The manufacturer provided us with flash code definitions to help diagnose problems.

Reduced Airflow Tests

The results of the reduced airflow tests are shown in Figure 25. The results of the one-third reduced airflow test show a slight, but insignificant, decrease in performance. The results of the two-third reduced airflow test show a more significant performance reduction, ranging from 5% to 20% over the course of the heating cycle.

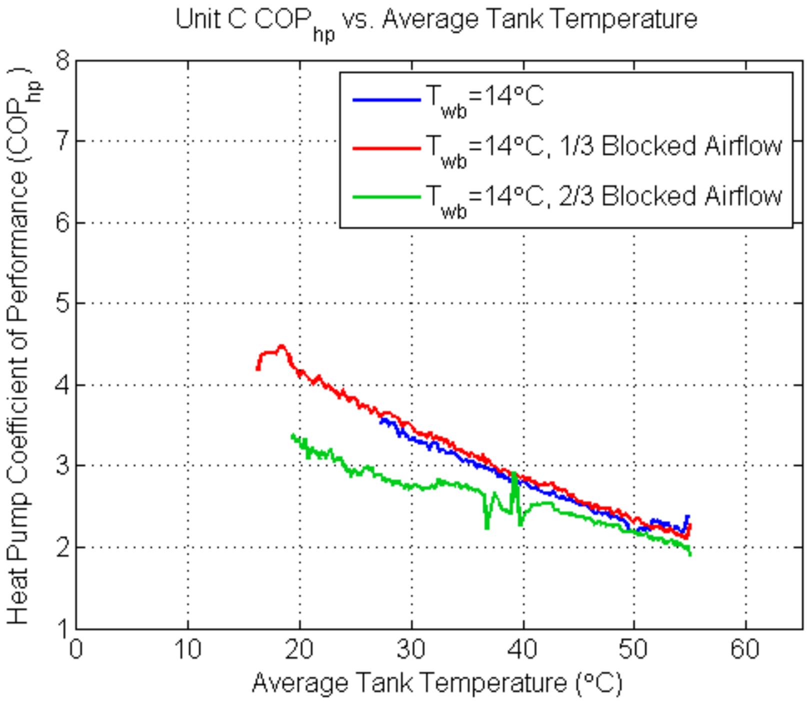


Figure 25. COP$_{hp}$ traces for Unit C with reduced airflow

Anomalies

The heat pump design appears to be optimized for speed at the expense of the operating range. The compressor is oversized, which results in fast recovery times, but also contributes to a more limited ambient temperature operating range. For air temperatures below ~15°C, icing starts to accumulate on the evaporator coils and the compressor will cycle on three times before switching over to the electric resistance elements to heat the water. In addition, when air temperatures are at or above ~38°C, the heat pump will cycle on once and then turn off in favor of the electric resistance elements. As mentioned previously, this is due to control logic that shuts off the heat pump if the temperature difference across the compressor is less than 20°C. (The reason for this restriction is still unknown and may or may not be a result of the oversized compressor.) These restrictions greatly limit the operating environments where this HPWH will be an efficient water heating option. In particular, garages and other unconditioned (or passively-conditioned) spaces may be poor locations for this unit.

Another result of the heat pump being designed for speed is that the upper resistance element must come on in place of the heat pump to finish the heating cycle. The refrigerant used in Unit C's heat pump, R-410a, operates at a higher pressure than R-134a. At the higher refrigerant temperature, this pressure starts to approach the maximum capacity of the copper tubing in the heat pump. Design changes could prevent the need for the electric resistance elements at the higher tank temperatures, such as reducing the diameter of the copper tubing, but these changes may slow the recovery time for the system.

System Drawbacks

Below is a list of system drawbacks that could be improved upon to enhance the capabilities of Unit C:

1. **Condenser design is ineffective.** The circulation pump that brings water to the coaxial heat exchanger at the top of the unit was found to be a detriment to the outlet temperature. For example, when performing water draws, the circulation pump mixes the cold water at the bottom of the tank with the hot water at the top of the tank, limiting availability of water at the desired (a.k.a. set point) temperature. It is assumed that the pump is needed to achieve sufficient (forced) convection in the coaxial condenser and prevent the water from boiling.

2. **Inefficient circulation pump.** The circulation pump draws ~70 W and produces enough heat to burn someone who touches it. This wastes energy and is a safety risk if the outside cover that protects the circulation pump is ever removed. If the pump could be moved to inside the heat pump compartment, this would reduce the safety risk and allow the heat pump to reabsorb the heat generated by the circulation pump.

3. **Control logic consists of long delay before compressor starts up**. The compressor in this unit has a starting delay of 20 minutes, presumably for internal diagnostics. This does not seem to be necessary. The long delay also might make homeowners think that something is wrong with the heat pump and switch its operating mode to all resistance heat to make sure that water will be heated.

4. **Control logic restricts upper range of operating conditions.** The heat pump will not run at air temperatures above ~38°C. Since this range also represents the range in which the heat pump could be most effective, the control logic should be reconsidered so the heat pump can operate at higher air temperatures. It is also unclear why this restriction was implemented by the manufacturer, from either a safety or performance perspective.

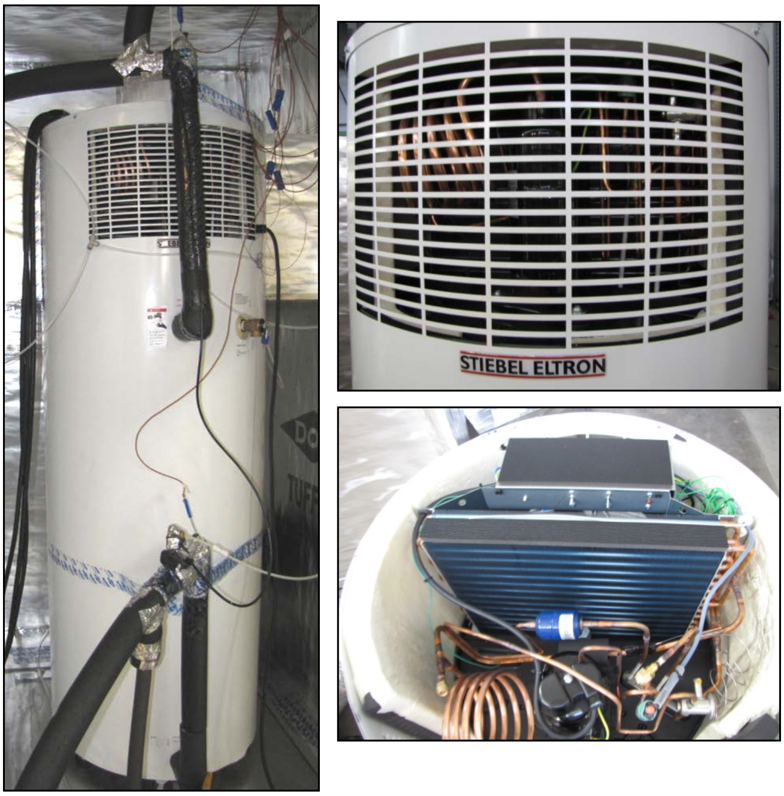
5. **Excessive icing occurs on the evaporator coils at moderate air temperatures.** Frequent icing occurs at air temperatures less than 20°C, making this unit an unfavorable choice for unheated or passively heated installation locations in cooler climates. This appears to be a result of using a larger compressor to speed recovery time.

6. **The upper resistance element is needed to achieve set points above 49°C**. As mentioned above, the design of the heat pump necessitates the use of the upper element at higher tank temperatures (and thus higher refrigerant temperatures) to avoid reaching the maximum pressure of the copper tubing.

Unit D HPWH Summary

Overall Impressions and Observations

Unit D is a simple HPWH with only one operating mode and no control panel. Where other companies have created many options and interactive displays, Unit D's manufacturer took the opposite path. There is only one operating mode and no way to turn the unit off. The controls for changing set point temperature are difficult to access, making it unlikely that users will ever adjust the default setting. There is a single, small electric resistance heater located near the hot water outlet, designed to provide a small amount of boost heating but the resistance heater alone could not be used to heat the entire tank. The large tank can provide plenty of hot water, but the heat pump and back up element are small, and so recovery time is slow. However, this unit has a high energy factor (EF) rating and so can provide very efficient water heating.



NREL/PIX 18676, 19460, and 19461
Credit: Kate Hudon

Figure 26. Unit D, an 80 gallon HPWH, installed in the test plenum (left). A close up of the air intake (top right) and the heat pump (bottom right) are also shown.

Installation and Usability Considerations

Unit D's inlet and outlet water lines are located on the side of the tank. The 80 gallon unit tested was just over 6 ft tall. The air enters the unit from the front, is pulled across the evaporator coils located in the middle of the heat pump, and exits out the back of the unit. There is no air filter in this unit. Currently, Unit D is not available through a major retailer, but can be purchased through plumbing suppliers.

There are no operating modes for Unit D and it is intended to be hard wired when installed, meaning that the user cannot manually turn the unit on or off. There are knobs located inside on the control board that can be used to change the temperature set point for the heat pump and electric resistance heater separately. However, the top of the heat pump case must be removed to access these knobs and there are no labels on the knobs to indicate the temperature range available or to identify which heating source they control. For laboratory testing, Unit D was wired to a switch for power and, when switched on, the fan and compressor turned on immediately. Since the default set point for the heat pump is 60°C and it is unlikely that the set point will be changed due to the inaccessibility of the controls, some tests were done with this set point to capture the more likely operating conditions.

Qualitative Test Results and Observations

The descriptions below explain the results of the tests run on Unit D and the observations made during testing.

Operating Mode Tests

Unit D has a single thermistor as a control input, located at the top of the tank. There is only one operating mode for this unit. The heat pump can operate at the same time as the electric resistance element, but the electric element cannot run on its own. There are two separate set points for the heat pump and resistance element. There are knobs to adjust these set points inside the heat pump casing, on the control board. Based on our tests, the compressor set point can vary between 54°C and 60°C and the resistance heater set point temperature has a range from 29°C and 57°C. There are no markings to indicate the current set point for either heat source.

Operation Mode description:

1. On: The heat pump will turn on when the thermistor registers a small drop in temperature (2°C) from the heat pump set point. The heating element will turn on when the top of the tank drops 5°C from the element set point. When the draw is large enough to trigger the heating element, it will remain on until the thermistor reaches the heating element set point. The default element set point is 55°C, which is below the default heat pump set point of 60°C. The rest of the tank will be heated with the heat pump until the thermistor reading reaches the heat pump set point. According to the user manual, the operating range for this water heater is between air temperatures of 6°C and 42°C.

Draw Profile Tests

Draw Profile 1 was tested in two parts. Unlike the other units where the draw profile tests were done with a 49°C set point, the set point for Unit D cannot be set below 54°C and it is unlikely that users will ever adjust the default set point of 60°C, so the draw profiles were run at the default set point temperature. During the morning portion of Draw Profile 1, four showers are simulated over the course of a little more than 1per hour. The outlet temperature through the first three remained close to 60°C but started to decrease during the fourth shower, with the outlet temperature falling to a minimum of 53°C. The heat pump turned on during the third shower and the electric resistance element turned on about an hour after the fourth shower was complete. The resistance element remained on for a half an hour, after which, the heat pump finished heating the tank to set point.

The evening draws produced outlet water at 60°C for the first half of the draws, but the outlet temperature started to drop by the end of the evening segment. The final draw delivered water at 54°C. The heat pump came on a little past the halfway point of the evening draw profile and remained on until set point was reached again.

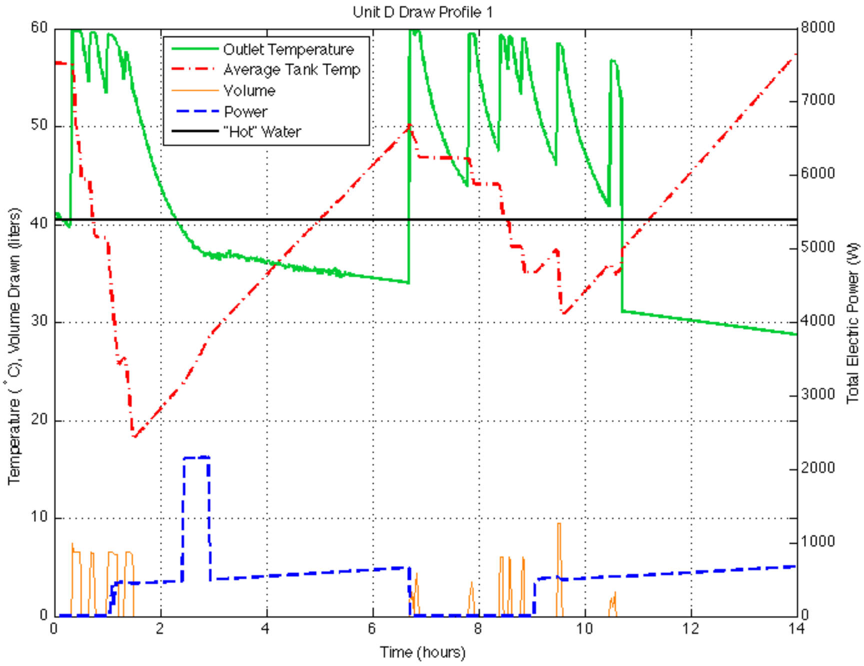


Figure 27. Draw Profile 1 for Unit D

Draw Profile 2 consisted of many small draws over a 6-hour period. Unit D performed well for this low-demand situation. The compressor turned on to reheat the tank about 3-½ hours into the 6-hour profile.

COP_{hp} Tests

The results of the COP_{hp} tests are plotted below in Figure 28. As expected, COP_{hp} increases as the inlet air temperatures rise and the COP_{hp} decreases as the water temperature in the tank increases. The electric resistance heater was disabled during these tests to ensure that it would not turn on. Even though COP_{hp} decreased for lower air temperatures, Unit D maintained a consistently high level of performance for all air conditions tested.

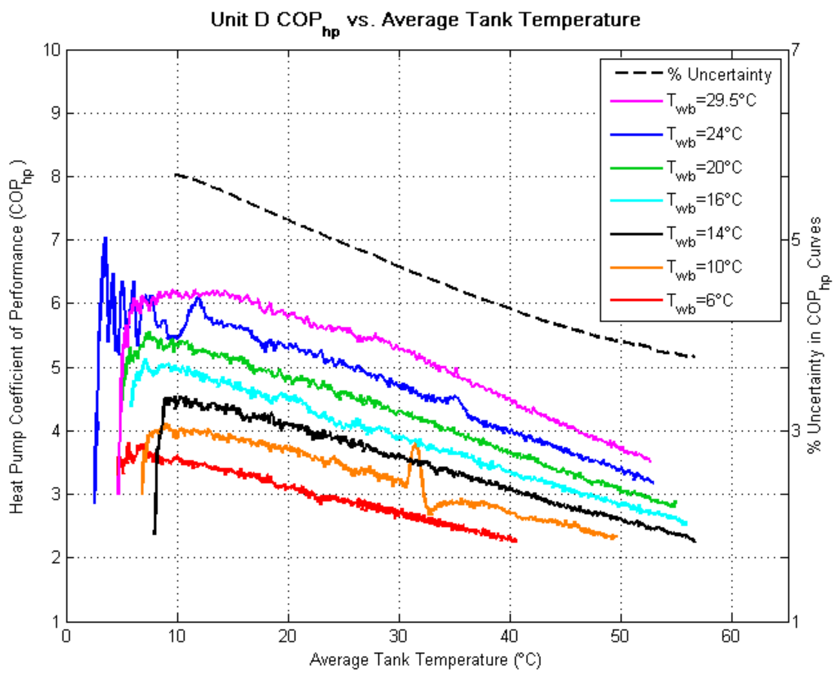


Figure 28. COP$_{hp}$ traces for Unit D

The two warmest COP$_{hp}$ tests were repeated with the same inlet dry bulb temperature for high and low relative humidity. Figure 29 shows this comparison for the inlet dry bulb condition at 35°C with the relative humidity at 40% and 19%. The corresponding wet bulb temperatures for these conditions are 24°C and 17°C, respectively.

The results in Figure 29 show that the performance increases were small for the COP$_{hp}$ test run at the higher inlet wet bulb temperature. For the lower tank temperatures, a difference in COP$_{hp}$ of approximately 5% can be seen. As the tank temperature increases, the performance difference drops to about 2%. The tank recovery time is shown in Figure 30. A reduction in recovery rate from 8.1°C/hr to 7.7°C/hr was observed in the lower humidity case. These results show that humidity has a small impact on the performance of this unit.

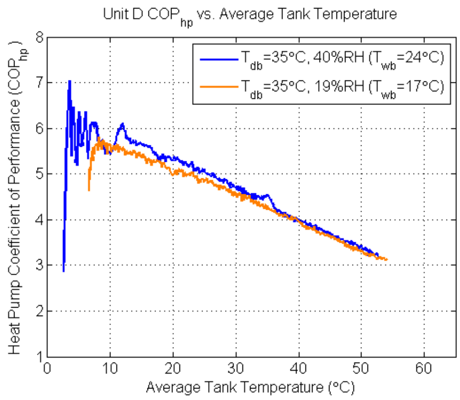


Figure 29. Effect of humidity on COP_{hp} for Unit D

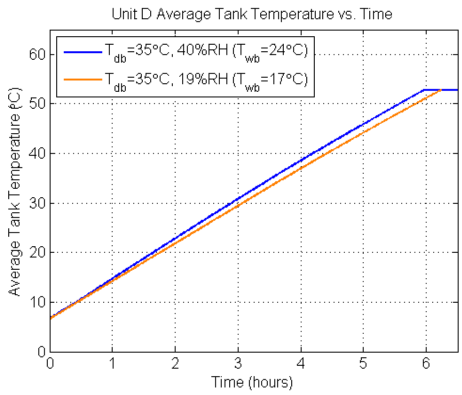


Figure 30. Effect of humidity on recovery time for Unit D

Reduced Airflow Tests

The results of the reduced airflow tests are shown in Figure 31. The results of the one-third airflow blockage test showed an insignificant decrease in performance. The results of the two-thirds airflow blockage test showed a slight decrease in performance, ranging from ~3% to ~4 % over the course of the heating cycle.

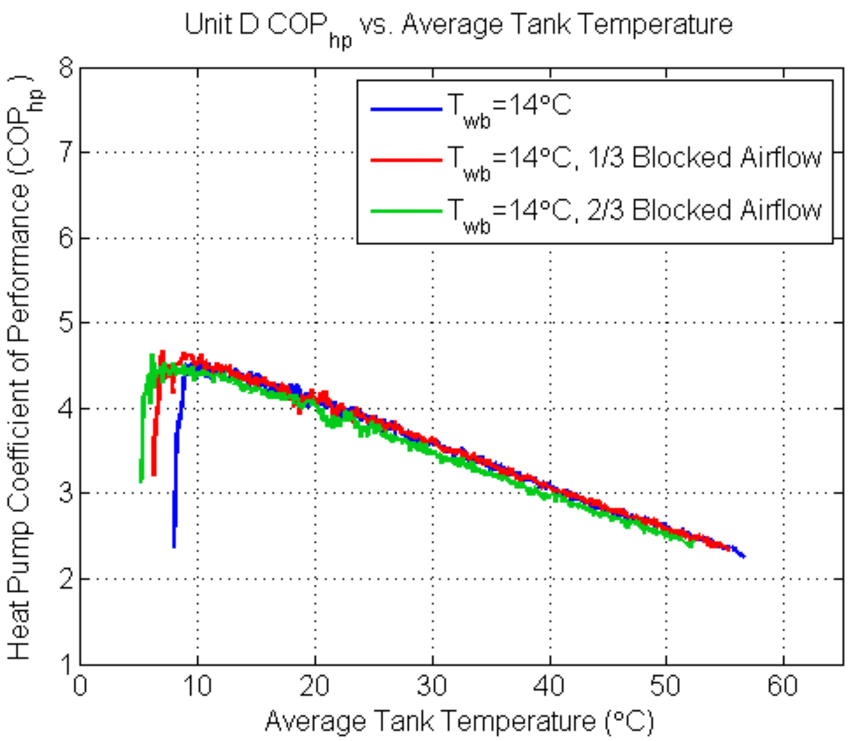


Figure 31. COP_{hp} traces for the Unit D with reduced airflow

System Drawbacks

Below is a list of system drawbacks that could be improved upon to enhance the capabilities of Unit D:

1. **The 80 gallon unit is tall.** The large tank capacity has many benefits from a performance perspective, but its physical size may limit the homes in which it can be installed. Unit D is over 6 ft tall and it could be limiting depending on where the hot water heater is installed in the home.

2. **Tank recovery does not start fast enough.** While the large tank provides ample hot water, reheating the tank is very slow. Rather than having the heat pump turn on after a small or moderate volume draw, Unit D waits to turn on both the heat pump and electric resistance heater until almost all the hot water in the tank has been drawn. This will result in very long recovery times during which no hot water will be available to the homeowners.

3. **There is only one operating mode.** Unit D has only one operating mode. Users may see this as a disadvantage since they cannot change modes in anticipation of higher hot water demand (having guests, for instance). The advantage to having only one operating mode is that users will be unable to switch to using all resistance heat by accident, but the lack of options will likely be seen as a disadvantage from the consumer's perspective.

4. **Means of controlling set point temperatures are inaccessible.** The knobs used to control heat pump and resistance heater set point temperatures are only accessible by taking off the top of the water heater casing. Even then, the knobs are not very obvious and there are no markings to indicate current set point and available range of set points. The default values will likely never be changed, even though the heat pump set point is 60°C, which is higher than the recommended set point temperature.

Unit E HPWH Summary

Overall Impressions and Observations

Unit E uses immersed condensing coils to reduce recovery time and provides an option to duct the outlet air. The heat pump operates over a wide ambient temperature range and has a defrost feature that allows it to operate in very cold air temperatures without reverting to the electric resistance element. However, the user interface is difficult to operate and the air filter is nearly inaccessible. Unit E also provides an option to duct the outlet air, which adds a degree of flexibility. Taking advantage of the outlet duct option would add to installation costs, but sending the cold outlet air out of the house or to the existing HVAC ducts in the house could add value to the water heater installation and eliminate some of the negative impact on the home's heating system in colder climates. A preproduction model of the Unit E HPWH was provided by the manufacturer for these tests and as such, some features and functionality will be modified in the full production model.

NREL/PIX 18919, 19462, and 19463
Credit: Kate Hudon

Figure 32. Unit E installed in test plenum (left). Some of the refrigerant system is shown (upper right), along with the blower that is designed to connect to a 6 in. duct (lower right)

Installation and Usability Considerations

Unit E's inlet and outlet water lines are located on the side of the tank. The 66 gallon unit that was tested is nearly 6 ft tall. There also is a 50 gallon version of Unit E that is a little less than 5 ft tall. The 66 gallon unit tested requires an airflow rate of about 300 cfm. The air enters the unit from the right (when viewed from the front), is pulled across the evaporator coils located in the middle of the heat pump, and exits out the top of the unit on the left side. This unit is designed to allow the outlet air to be ducted so the unit has a blower instead of a typical axial fan. Ducting the outlet air would be useful in both hot and colder climates. If installed in a home in a hot climate that has a central air conditioning system, a duct could be used to route the cold outlet air from the HPWH to the existing duct system in the house. Additionally, in colder climates, the duct could be used to send the outlet air outside, so as not to add to the heating load during the winter time. This would add to the cost and complexity of installation but it could improve the HPWH's impact on the HVAC system. The air filter is only accessible if the heat pump cover is removed. If the outlet was ducted, it would be impossible to remove the heat pump cover without disassembling the duct. Even if the ducting option was not in use, the heat pump cover is not easily removed and power must be disconnected, making it very unlikely that any users will ever clean the air filter. Currently, Unit E is not available through a major retailer.

The user interface displays temperature settings, as well as current air and water temperature readings, and can be used to change a number of options. There are three operating modes: Econ (heat pump only), Auto (combination heat pump and electric resistance heat), and Heater (all electric resistance heating). There are indicators on the user interface to show when the unit is actively heating and what heat source(s) are being used. However, the usability of the interface is poor, making it difficult to perform simple tasks like changing the set point temperature. One unique control feature is that the user can set time periods that restrict when the heat pump will operate in Econ mode. This may be a nice feature for advanced users, but there is no default time period, so if Econ mode is selected and operating periods have not been defined, the heat pump will never turn on. This feature may discourage users from using the most efficient mode.

This unit contains two 4 kW electric resistance heaters but only one of them will be used during normal operation. The second resistance heater is wired for power separately from the main power supply, so it will never turn on in typical installations. According to the manufacturer, the second resistance heater should only be used if the primary electric heater fails. The backup resistance heater sits just below the midpoint of the tank and the primary resistance heater sits above that, a third of the height of the tank from the top.

Qualitative Test Results and Observations

The descriptions below explain the results of the tests run on Unit E and the observations made during testing.

Operating Mode Tests

Unit E has two thermistors that are monitored to control the heat pump and electric element. The lower thermistor is located just above the unused back up resistance heater, at roughly the mid-point of the tank. The upper thermistor sits above the usable resistance heater and is halfway between the top of the tank and the lower thermistor. The lower thermistor is used to control the heat pump and the upper thermistor controls the resistance element. The resistance element and heat pump can operate simultaneously.

Operation Modes and description:

1. <u>Econ Mode:</u> The heat pump will turn on when the lower thermistor measures a temperature of 10°C–15°C below the set point. The heat pump will turn off when the

lower thermistor returns to the set point. The deadband can be adjusted by the user through the user interface. According to the manufacturer, the default deadband is 5°C but heat pump operation was triggered by larger temperature drops during laboratory tests. At a set point of 49°C, a 10°C drop in temperature at the lower thermistor caused the heat pump to turn, while at the 57°C set point, a 15°C drop was required for the heat pump to turn on. Even though a relatively large draw is required to trigger the heat pump, the heating capacity of the heat pump is large enough to recover in a short amount of time.

- A timer period must be defined by the user for the heat pump to turn on at all in this mode. However, if one or more timer period is set, the heat pump operates well across the operating range.
- If the air temperature is cold enough to cause icing on the coils while the heat pump is operating, a defrost cycle will occur. The fan is turned off for about 2 minutes while the compressor remains on and the refrigerant reversing valve reheats the evaporator coil (now the condenser) to melt the ice. This process is repeated as needed until set point has been reached or until icing is no longer a problem.

2. Auto Mode: As with Econ mode, the heat pump turns on once the lower thermistor measures a temperature drop from set point of 10°C–15°C. A larger draw will trigger the electric resistance heater. The resistance heater will turn on when the upper thermistor measures a drop in temperature of 10°C–20°C and will turn off when the upper thermistor is at set point. The resistance heater will operate at the same time as the heat pump. If the resistance heater is called for, the heat pump will remain on and will continue to heat the tank until the lower thermistor reaches set point. Unlike Econ mode, a timer period does not need to be set for the heat pump to operate.

3. Heater Mode: This mode will only use the resistance heating element to heat the tank. Similar to the control of the resistance element in Auto mode, the resistance heater will turn on when a drop in temperature of 10°C–20°C degrees is detected by the upper thermistor. The electric element is located in the upper third of the tank so, in Heater mode, only the top third of the tank will be heated. This mode will not satisfy hot water demands for most users and is the least efficient of all modes. Heater mode is only intended to be used when the heat pump is not functional.

Draw Profile Tests

Draw Profile 1 was tested in two parts. During the morning segment of Draw Profile 1, four showers are simulated over the course of a little more than an hour. Unit E unit was able to maintain an outlet temperature of 49°C during the first three showers, but dropped below 40.5°C during the fourth shower. By the end of the fourth shower, the outlet temperature had dropped to about 38°C. The heat pump turned on during the second draw and remained on for the rest of the morning segment until set point was reached. The electric resistance heating element turned on during the third shower when average tank temperature started to drop. The evening draws were completed with no significant dip in outlet temperature. The heat pump turned on about halfway through the evening portion and remained on until the set point was achieved after the profile finished. The upper resistance element also turned on for a brief time following the next to last draw.

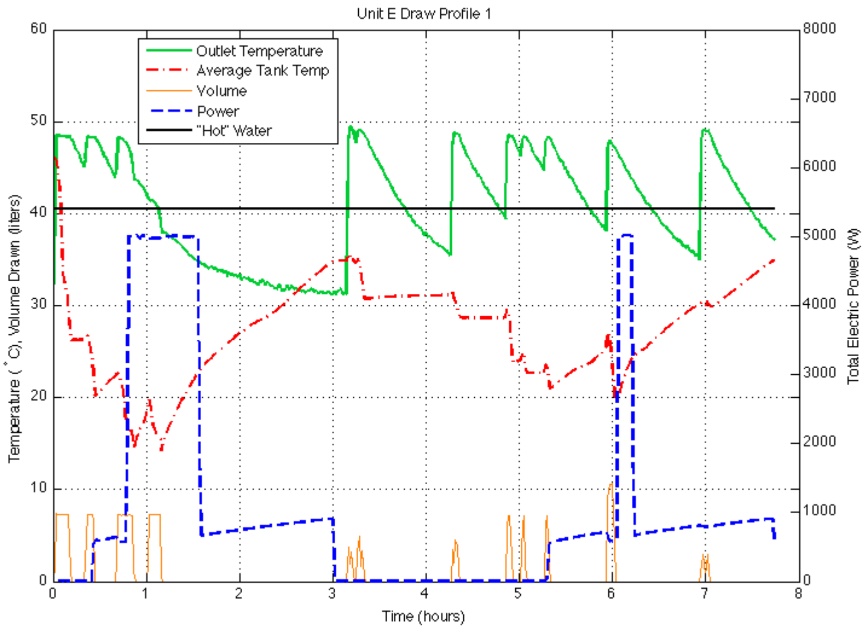


Figure 33. Draw Profile 1 for Unit E

Draw Profile 2 did not provide any additional insight about the performance of the previous HPWHs tested, so it was omitted from Unit E's test schedule.

COP_{hp} Tests

The results of the COP_{hp} tests are plotted below in Figure 34. As expected, COP_{hp} increases as the inlet air temperatures increases and the COP_{hp} decreases as the water temperature in the tank increases. These tests were run in Econ mode to ensure heat pump-only operation. At the lowest air temperatures, the defrost cycle was needed to prevent icing on the coils. During the defrost cycle, the fan is turned off for 2 minutes while the compressor remained on. The periods of defrost can be seen in dips in the lowest wet bulb temperature COP_{hp} curves.

An additional cold air test was partially completed at 4.5°C dry bulb and 3°C wet bulb. Since this test article claimed better cold weather performance than all the others, this additional test point was added. By the time the tank temperature reached 27°C, it became impossible to maintain the air conditions due to laboratory limitations. The test did confirm that this unit can operate below 7°C, the lower limit for ambient temperature for all of the other units, even though repeated defrost cycles were required.

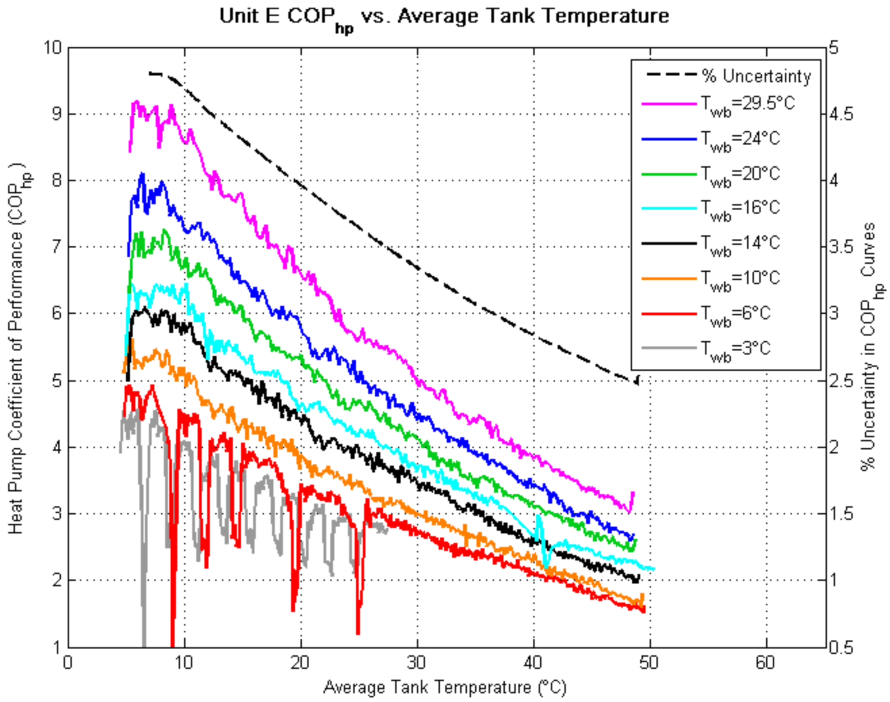


Figure 34. COP_{hp} traces for Unit E

The COP_{hp} test run at the highest dry bulb temperature was repeated with a lower relative humidity to determine the impact of humidity on performance. Figure 35 shows this comparison for the inlet dry bulb condition at 35°C with the relative humidity at 40% and 19%. The corresponding wet bulb temperatures for these conditions are 24°C and 17°C, respectively. There was a significant performance difference between the dry and humid air conditions, especially at the lower tank temperatures. The tank recovery time is shown in Figure 36. This shows that the higher humidity case resulted in an increase in recovery rate from 10.8°C/hr to 11.8°C/hr.

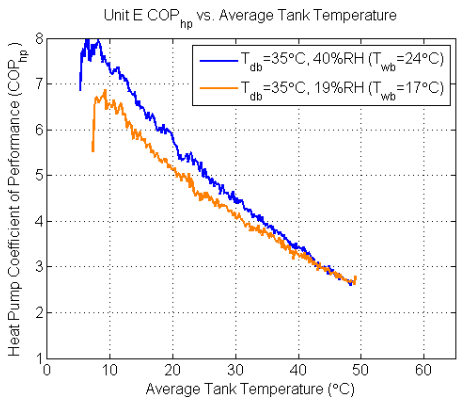


Figure 35. Effect of humidity on COP$_{hp}$ for Unit E

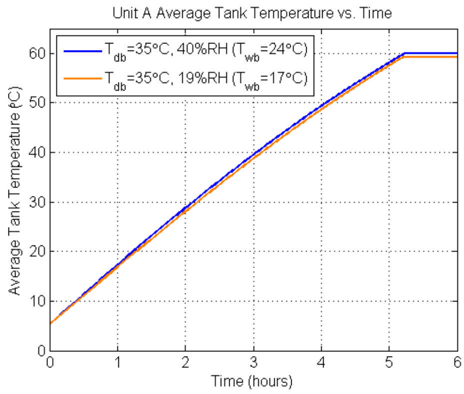


Figure 36. Effect of humidity on recovery time for Unit E

Reduced Airflow Tests

The results of the reduced airflow tests are shown in Figure 37. Since the four previous units tested showed little to no impact when one-third of the inlet area was blocked, that test was omitted for Unit E. The two-thirds airflow blockage test resulted in no noticeable performance degradation.

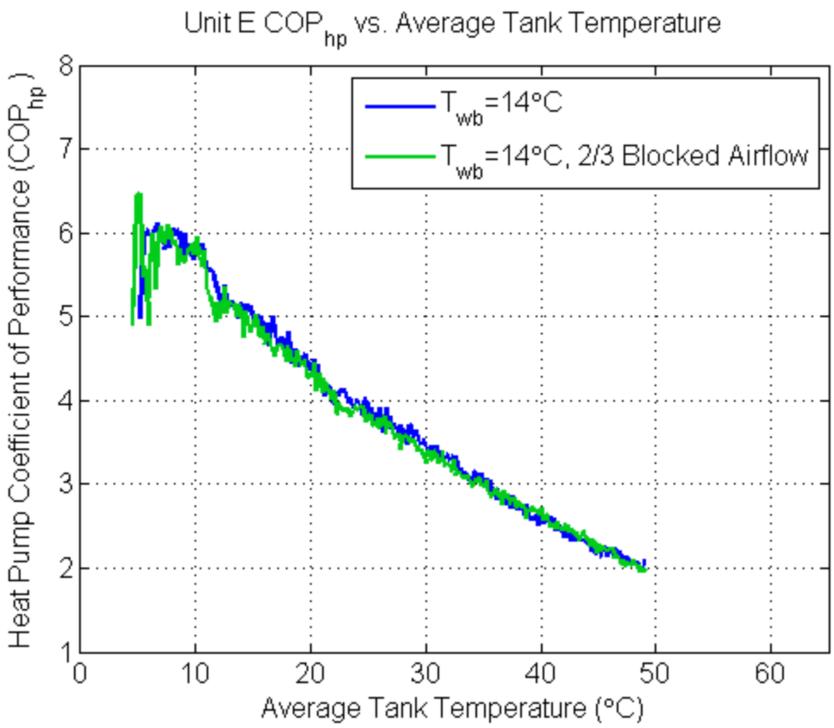


Figure 37. COP$_{hp}$ traces Unit E with reduced airflow

System Drawbacks

Below is a list of system drawbacks that could be improved upon to enhance the capabilities of Unit E. It should be reiterated that the unit tested was a preproduction model and some functionality is expected to be modified in the full production version.

1. **User interface is difficult to use.** Changing operating modes is straightforward since each mode has its own button, but any other action, including simple tasks like changing the set point temperature, are impossible without the manual.

2. **Internal condensing coils do not heat the bottom of the tank.** The bottom of the condensing coils sits about 8 in. above the bottom or the tank, meaning that about 8 gallons of water at the bottom of the tank remain cold even when the heat pump is on. This effectively reduces the tank capacity from 63 gallons (as measured) down to 55 gallons.

3. **Backup resistance element is too high in the tank.** The backup electric resistance element sits about one third of the tank height from the top of the tank. When in Heater mode, the resistance heater can only heat the top third of the tank. Heater mode is not intended to be used unless the heat pump malfunctions, but if that was to happen, this water heater may not be able to provide sufficient hot water.

4. **Timer feature will likely cause more harm than good.** Up to three time periods can be set for heat pump operation when in Econ mode. If the heat pump is called for at a time outside of these ranges, it will not turn on. This feature is designed to allow homeowners to control when cold air is generated by their water heater. However, there is not a default timer period, so if the user tries to use Econ mode without setting a time period, nothing will happen.

5. **Extra resistance heating element is unnecessary.** Unit E comes with a second, back-up resistance heating element that is only used if the main resistance heater fails. In fact, the second resistance heater has a separate power supply that must be wired separately for use. This seems like an unnecessary feature that just increases its cost. Also, the back-up resistance element sits lower in the tank than the main resistance element. If it was eliminated, the main resistance element could sit lower, allowing it to heat a larger portion of the tank.

6. **Air filter is inaccessible.** The air filter is located under the heat pump casing and cannot be accessed without fully disassembling the case and the outlet ducting (if in use). Users will likely never clean the air filter unless it is easily accessible.

Data Comparison and Analysis

Operating Mode Control Comparison

The following table summarizes the control logic for each operating mode for each test article. More detailed information about each unit's control logic can be found in the specific water heater sections, but the tabular format allows for quick comparison between different units.

Table 3. Comparison of Operating Modes and Control Logic for All Five Units

	Unit A	Unit B	Unit C	Unit D	Unit E
Most-efficient mode:	Efficiency	eHeat	EnergySaver	On	Econ
Heat pump?	Yes	Yes	Yes	Yes	Yes
Control logic to turn on heat pump:	$\Delta T_{tank,mfr} = -5°C$[1]	$\Delta T_{upper} = -0.5°C$	$T_{lower} = 22°C$	$\Delta T_{upper} = -2°C$	$\Delta T_{lower} = -10°C$
Resistance elements?	No	No	Yes	Yes	No
Control logic to turn on heating elements:	-	-	$T_{lower} = 22°C$[2]	$\Delta T_{upper} = -10°C$[3]	-
Hybrid Mode:	Hybrid	Hybrid	Normal	N/A	Auto
Heat pump?	Yes	Yes	Yes	-	Yes
Control logic to turn on heat pump:	$\Delta T_{tank,mfr} = -5°C$	$\Delta T_{upper} = -0.5°C$	$T_{lower} = 22°C$	-	$\Delta T_{lower} = -10°C$
Resistance elements?	Yes	Yes	Yes	-	Yes
Control logic to turn on heating elements:	$\Delta T_{tank,mfr} = -10°C$[5]	$\Delta T_{upper} = -10°C$[4]	$T_{lower} = 22°C$	-	$\Delta T_{upper} = -10°C$
Additional Mode:	N/A	High Demand	N/A	N/A	N/A
Heat pump?	-	Yes	-	-	-
Control logic to turn on heat pump:	-	$\Delta T_{upper} = -0.5°C$	-	-	-
Resistance elements?	-	Yes	-	-	-
Control logic to turn on heating elements:	-	$\Delta T_{upper} = -3°C$	-	-	-
Resistance-only Mode:	Electric Only	Electric Only	Electric Only	N/A	Heater
Heat pump?	No	No	No	-	No
Control logic to turn on heat pump:	-	-	-	-	-
Resistance elements?	Yes	Yes	Yes	-	Yes
Control logic to turn on heating elements:	$\Delta T_{tank,mfr} = -2°C$	$\Delta T_{upper} = -0.5°C$	$T_{lower} = 20°C$	-	$\Delta T_{upper} = -10°C$

Table 3 Notes:

1. Unit A uses following equation for control:

$$T_{tank,mfr} = (3 * T_{upper} + T_{lower})/4$$

2. The upper heating element will turn on concurrently with heat pump in EnergySaver mode and Normal mode if tank set point is ≥54°C.

3 The heating element and heat pump can run at the same time. Once called for, the heating element will remain on until T_{upper} reaches the heating element set point, which is set separately from the heat pump set point.
4 If heating elements are called for in Hybrid or High Demand mode, the heat pump will not turn on again. The heating elements will be used exclusively to finish the heating cycle.
5 Upper element and heat pump cannot operate simultaneously. When the controller calls for the upper element, the heat pump turns off until T_{upper} reaches set point. Then the heat pump will turn back on to finish heating the tank.

COP_{hp} Test Results Comparison

The COP_{hp} tests were performed to determine the performance of the HPWH operating with the heat pump alone. This allows the units to be compared against each other as they operate under various average tank temperatures. Figure 38 shows a comparison of the COP_{hp} curves for the five integrated HPWHs for the inlet wet-bulb air temperature of 14°C (67°F).

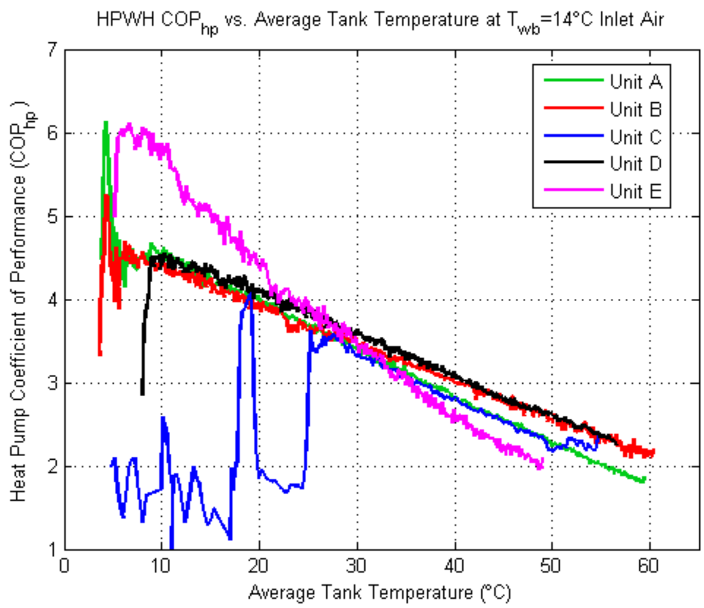


Figure 38. COP_{hp} comparison for five HPWHs at 14°C inlet wet bulb air temperature

This comparison shows that the COP_{hp} curves for Units B and D are very similar, both in shape and magnitude. Unit A is also similar to Units B and D in the lower range of average tank temperatures, but the performance drops off more significantly at the higher tank temperatures. Unit E performed very well at lower average tank temperatures, but the slope of the curve is greater, resulting in lower performance than the other units at the higher average tank temperatures. It should be noted that the shapes of the curves appear to depend on the type of refrigerant used. Units A, B and D use R134-a and their COP_{hp} curves have a linear characteristic shape. Units C and E use R410-a and their COP_{hp} curves decay exponentially. Another explanation for the similar shapes of Unit C and E is that the heat transfer from the refrigerant and the water is more direct, whereas the other three units have to transfer heat through the wall of the copper tubing and the wall of the tank before getting to the water. It should also be noted that a typical range of average tank temperatures for a water heater in a home is between 40°C and 50°C. Over this range, Units B and D have the best performance in terms of energy efficiency.

Another key performance consideration is the heating capacity of the heat pump. Figure 39 shows a comparison of the heating capacity for the five integrated HPWHs for the inlet wet-bulb air temperature of 14°C.

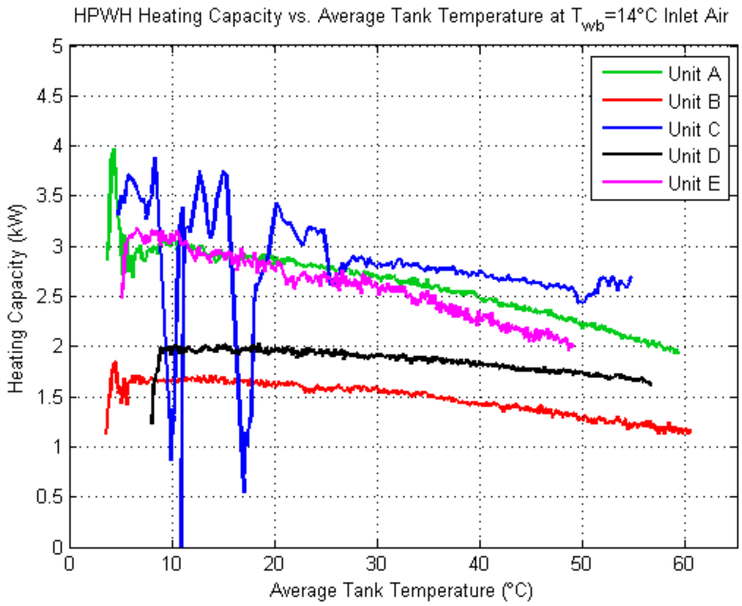


Figure 39. Heating capacity comparison for five HPWHs at 14°C inlet wet bulb air temperature

This comparison shows that the Units B and D have the lowest heating capacity, so although they are very efficient at the higher average tank temperatures, they will take longer to reheat than the other units. The heating capacity curve for Unit C, much like the COP_{hp} curve, is irregular until the average tank temperature reaches about 25°C because the heat pump could not sustain operation due to icing at the lowest tank temperatures.

In the end, a homeowner should weigh energy efficiency with thermal performance. For homes with low hot water demand, the high efficiency, low heating capacity units should be able to satisfy demand and provide highly efficient water heating. For high use situations, heating capacity and tank volume may become more important factors.

Draw Profile System COP_{sys} Comparison

COP_{sys} values were calculated for the morning and evening portions of Draw Profile 1 and for Draw Profile 2. The purpose of these calculations is to determine realistic performance numbers for the units tested.

As mentioned previously, the morning portion of Draw Profile 1 was designed to represent a high demand situation. All test articles, except for Unit A, resorted to electric resistance supplemental heaters. The evening portion of Draw Profile 1 was designed to represent the evening hot water use for a typical household. These draws are spaced further apart than the morning draws and therefore represent a medium demand situation. For the smaller tank units,

Units B, C, and E, the electric resistance elements were needed to supplement the heating process.

Draw Profile 2 represented a low demand situation spanning across 6 hours. None of the HPWHs used back-up electric resistance heat to supplement the reheat cycle. Since COP_{sys} can be estimated using the COP_{hp} curves for Draw Profile 2, it was decided not to run this profile for Unit E.

Table 4. Draw Profile System COP_{sys} Values

HPWH Mfr.	COP_{sys} (DP1 – Morning)	COP_{sys} (DP1 – Evening)	COP_{sys} (DP2)
Unit A	3.55 ± 0.08	3.42 ± 0.08	2.62 ± 0.06
Unit B	1.21 ± 0.03	1.81 ± 0.05	3.46 ± 0.06
Unit C	1.44 ± 0.04	2.61 ± 0.06	2.53 ± 0.05
Unit D	3.85 ± 0.06	5.37 ± 0.05	3.09 ± 0.06
Unit E	1.68 ± 0.05	2.77 ± 0.07	N/A

The results from the Draw Profile COP_{sys} tests are shown in Table 4. It should be noted that these tests include the standby losses incurred by the tanks during the test. The morning results show that the units with the smallest tanks, Units B and C, had the lowest COP_{sys} values. These units had a difficult time keeping up with demand and had to rely extensively on the back-up electric resistance heating elements. Unit D had the highest COP_{sys} for the morning draw profile. This can be attributed to both its large storage tank and the small heating capacity of its heat pump. The other two units performed as expected based on the sizes of their storage tanks.

For the evening portion of Draw Profile 1, all the HPWHs except Unit E performed better than they did in the high demand situation of the morning draws. Unit B has the lowest COP_{sys} due to its control logic, which did not switch back to the heat pump once the electric resistance elements are enabled, due to the combined size of the draws. Units C and E had modest increases in COP_{sys} during the evening portion of Draw Profile 1 because the electric resistance heating elements were used less than for the morning draws. Unit A experienced a slight decrease in COP_{sys}. It is expected that these numbers are similar because Unit A did not need its electric resistance heat for either of these profiles. It is slightly greater for the case of the morning draws because average tank temperatures dropped lower than in the case of the evening draws because of the high density of draws, resulting in a higher COP_{sys}. Unit D had the greatest COP_{sys} during the evening segment because it did not turn on its heating element and its heating capacity is low.

The COP_{sys} values for Draw Profile 2 are similar to the COP_{sys} values that can be obtained from the COP_{hp} curves that define the heat pump performance. There is also little difference in performance across the four units that performed Draw Profile 2.

Standby Heat Loss Coefficient Comparison

The heat loss coefficient, UA, indicates how much heat is lost to the ambient air. A large value for UA implies a poorly insulated tank or the presence of thermal shorts. Table 5 shows the standby heat loss coefficient for each HPWH as calculated during the Draw Profile tests.

Table 5. Standby Heat Loss Coefficient for Each HPWH

HPWH Mfr.	UA (kJ/hr/°C)
Unit A	7.11 ± 0.13
Unit B	9.60 ± 0.20
Unit C	7.39 ± 0.15
Unit D	8.74 ± 0.17
Unit E	6.23 ± 0.15

While all the UA values for the different HPWHs were found to be similar, it is also clear that some units are losing more heat to ambient than others. Unit B has the largest UA value, indicating a poorly insulating tank or many thermal shorts. On the other side of the spectrum, Unit E has the smallest UA, meaning that the tank is well insulated or has better management of thermal shorts.

Recovery Rate Comparison

One concern about HPWH technology is the slow rate of recovery to set point that could result in insufficient hot water to meet demand. As shown in Table 6, the recovery rate for a standard electric resistance water heater with 4.5kW of heating capacity is 22.3°C/ hr. This means that a standard 50 gallon water heater could recover from a series of large draws within an hour.

Table 6. Recovery Rate Comparison vs. Electric Resistance Water Heater

HPWH	Recovery Rate (°C/hr)	Percent Reduction vs. Electric (%)
Electric Resistance*	22.3	-
Unit A	8.5	62
Unit B	6.3	72
Unit C	13.2	41
Unit D	5.4	76
Unit E	9.6	57

*Note: From Energy Plus Simulation using 50 Gallon Electric Resistance Water Heater with a heating capacity of 4.5kW.

When comparing recovery rate between the standard electric water heater and the HPWHs, the difference is significant. Table 6 shows the recovery rates for the HPWHs when tested at 14°C inlet air wet-bulb temperature. The data used to calculate these values was taken from the operating mode Tests when water was drawn until the heat pump alone turned on and then the tank was allowed to recover. The data from these tests was used in place of the COP_{hp} tests since the HPWH were allowed to operate as they would normally, where some controls were overridden during the COP_{hp} tests. The intent was to capture heat pump-only operation, unless that operation rarely occurs, as with Unit C. The results show that recovery rates for HPWH vary between 5.4°C and 13.2°C, which correspond to a reduction in recovery rate relative to an electric resistance water heater of between 41% and 76%.

These reductions are significant, but are not expected to be detrimental to the technology if the storage tank is sized appropriately for the household. Households with large demands should use a HPWH with a large storage tank so that hot water is less likely to run out. In addition to the tank size, control logic is important, as was mentioned in the section describing the operating mode tests for each unit. As new manufacturers enter the market and as newer versions of the models tested become available, it will be difficult to know how the control logic is programmed before purchasing a HPWH. However, as future generations of HPWHs make their way to the market, the control logic will inevitably improve and cater to a range of hot water demands.

Cooling Capacity and Sensible Heat Ratio Comparison

The operation of the heat pump removes heat from the air through a vapor compression cycle that is similar to a conventional air conditioner. Therefore, operating the heat pump will have a certain cooling effect on its surroundings. This total cooling effect can be separated into a sensible and latent cooling capacity for each unit, as well as a sensible heating ratio (SHR), which is defined as follows:

$$SHR = {}^{q_s}/_{q_t}$$

where q_s is the sensible cooling capacity and q_t is the total cooling capacity. Table 7 shows the sensible and total cooling capacities for each of the HPWHs tested and the corresponding SHR at an inlet air wet bulb temperature of 14°C (57°F) and an average storage tank temperature of 48.9°C (120°F). Note the cooling capacity numbers and SHR will change with wet bulb temperature and tank temperature.

Table 7. Cooling Capacity and SHR Comparison

HPWH Mfr.	Sensible Cooling Capacity (W)	Total Cooling Capacity (W)	SHR
Unit A	1680	1704	0.986
Unit B	672	768	0.875
Unit C	905	1350	0.670
Unit D	1015	1027	0.988
Unit E	1048	1051	0.997

Biquadratic Coefficients for HPWH Modeling

The performance mapping data acquired during testing can be used to develop and validate simulation models that represent HPWH technology. One way to represent the data for COP_{hp} and compressor heating capacity is by using biquadratic curve fits. For HPWHs, these curves are defined using the following equation:

$$Performance\ Variable = C_1 + C_2 * T_{wb} + C_3 * T_{wb}{}^2 + C_4 * T_{wa} + C_5 * T_{wa}{}^2 + C_6 * T_{wb} * T_{wa}$$

where T_{wb} is the inlet air wet bulb temperature and T_{wa} is the average water temperature in the storage tank. The coefficients used to define the normalized COP_{hp} and heating capacity curves for the test articles can be found in Tables 8 and 9. The COP_{hp} and heating capacity equations were normalized by rated COP_{hp} and rated heating capacity, respectively. The rated values for each unit can be found in Table 10. The rated conditions are defined at a T_{wb} of 14°C (57°F) and a T_{wa} of 48.9°C (120°F).

Table 8. Coefficients for Normalized COP_{hp} Curve

HPWH Mfr.	C_1	C_2	C_3	C_4	C_5	C_6
Unit A	1.229E+00	5.549E-02	1.139E-04	-1.128E-02	-3.570E-06	-7.234E-04
Unit B	1.192E+00	4.247E-02	-3.795E-04	-1.110E-02	-9.400E-07	-2.657E-04
Unit C	6.945E-02	6.601E-03	1.598E-04	8.842E-04	8.170E-06	3.255E-05
Unit D	9.814E-01	5.334E-02	-2.802E-04	-3.073E-03	-1.384E-04	-2.897E-04
Unit E	2.168E+00	8.124E-02	4.786E-04	-4.870E-02	4.284E-04	-1.499E-03

Table 9. Coefficients for Normalized Heating Capacity Curve

HPWH Mfr.	C_1	C_2	C_3	C_4	C_5	C_6
Unit A	7.055E-01	3.945E-02	1.433E-04	2.768E-03	-1.069E-04	-2.494E-04
Unit B	5.050E-01	5.116E-02	-2.026E-04	5.444E-03	-1.154E-04	-2.472E-04
Unit C	6.879E-01	1.987E-02	7.659E-04	2.621E-03	5.323E-05	-5.210E-04
Unit D	5.101E-01	3.588E-02	5.563E-05	4.828E-03	-1.348E-04	7.738E-05
Unit E	9.285E-01	4.088E-02	2.737E-04	-3.625E-03	-6.521E-05	-2.986E-04

Table 10. Rated COP_{hp} and Heating Capacity

HPWH Mfr.	Rated COP_{hp}	Rated Heating Capacity (W)
Unit A	2.43	2350
Unit B	2.76	1380
Unit C	2.42	2670
Unit D	2.77	1820
Unit E	2.02	2040

It should be noted that these curves do not include the stand-by losses associated with the storage tanks. The stand-by losses were removed from the COP_{hp} calculation for the purposes of modeling inputs. Also, note that it is important to use the storage tank UA values to include the effect of stand-by losses when running an energy simulation.

A biqradratic curve fit was chosen to represent the COP_{hp} and heating capacity data so it could be easily incorporated into the energy simulation software, EnergyPlus (EnergyPlus 2010). A HPWH model currently exists in EnergyPlus, and has been evaluated with the data from the results for Unit B (Hudon 2012). The results of this evaluation show that the current model configuration in EnergyPlus does not accurately capture the energy used by the HPWH. Efforts are underway to improve this model for eventual incorporation into the whole-house energy simulation tool, BEopt (NREL 2011).

Conclusions

The laboratory results presented in this paper show that the HPWH is a promising emerging technology with the potential to significantly reduce the energy associated with generating hot water relative to standard electric water heaters. We conclude from these results that a HPWH can be used to save energy in all U.S. climates when compared to an electric resistance water heater, and that this technology would provide the most benefit in warmer climates due to the improved performance and space cooling/dehumidification effects. The results of the COP_{hp} tests show that heat pump performance is reduced at lower air temperatures, but even at these conditions, power consumption is roughly one-third to one-half that of a conventional electric resistance water heater when using the heat pump exclusively.

The performance results for HPWHs are promising, but another important factor is how they will be perceived by homeowners. One issue homeowners might encounter when using this technology is its lower rate of recovery in heat pump-only operation. This issue can be mitigated by choosing a tank size that is appropriate for the hot water demand of the household. It is suggested that existing water heaters be replaced only by HPWHs with the same or increased tank capacity. In addition, the various operating modes are designed to be changed based on the user's current need. Homeowners should become familiar with the user manual for the unit they purchase so the correct operating mode is selected.

Homeowners and installers must also be aware of the physical challenges associated with installing these units as well as their effect on the surrounding environment. HPWHs are larger than conventional water heaters and require a sizeable volume of air from which to draw heat. This imposes limits on the installation location and should be considered before purchasing a unit. If the physical requirements can be met, the surrounding environment must also be considered. In regions with a long heating season, it is not recommended that HPWHs be installed in conditioned space, particularly if space heating is provided via electric resistance. The garage could be an ideal location for this technology if freezing temperatures are not common. In addition, installation in an unconditioned basement can be considered as long as cooling the basement air is not a concern. Operating the heat pump can dehumidify the air around it, which could be an advantage in a basement environment. One other installation consideration is the presence of a drain. Operating the heat pump will result in condensation building up on the evaporator coils that needs to be directed to a nearby drain.

Some of the issues that were found with the HPWH technology can be improved upon as future generations are released. Three areas where improvements could be made include control logic, user interfaces, and ease of serviceably. It was found that the COP_{sys} of the HPWHs operating in their Hybrid modes varied across the models tested, mostly as a result of the differences in control logic. For example, some control schemes appeared to sacrifice efficiency in favor of shorter recovery times, while other strategies maintained efficiency by minimizing the use of the electric elements, which limited the volume of hot water available during high demand times. In addition to control logic, some of the units have user interfaces that are not intuitive or require toggling through multiple menus to make changes. This issue could be frustrating to a user, and result in a homeowner not changing modes at all. Also, if there is an issue with the operation of the heat pump, it is possible for the homeowner not to realize it because hot water will still be available as long as the back-up elements are functional. An effective means of detecting and informing the homeowner of faults or necessary service by an HVAC technician should be included on every unit.

Selecting the correct HPWH for a specific application can be challenging since advantages and disadvantages exist for each of the units that were tested. The results of this research are intended to provide guidance to homeowners and builders who are considering purchasing and installing a HPWH in a residential home. The following paragraph summarizes the findings of this research for the specific units that were tested.

In general, we found that Unit A performed well and was able to provide ample hot water because of its large tank volume and responsive control logic. The drawbacks of this unit include its high airflow rate and size, which may result in installation difficulty. Installation location must be considered carefully for this unit. Unit E performed well at low air and water temperatures and its exhaust airstream can be easily ducted. This makes it a good option for cold climates. The drawbacks to this unit are the non-intuitive user interface, the inaccessible air filter, and lack of heat pump access for servicing. Unit B also performed well, but was not as consistent at delivering hot water to the end user because of its smaller tank volume. For low demand situations or when tank size is an installation concern, Unit B would be a good option. Unit D was the most efficient of the HPWHs tested, but it also was the slowest unit to recover, the electric resistance element was not helpful in high-demand situations, and the set point is difficult to change. In addition, it only has one operating mode. Unit C performed well, but only within a limited range of operating temperatures. Due to this limitation, this unit is expected to be less efficient when used in cold or hot climates unless installed in conditioned space. Due to its small storage tank and water circulation pump, this unit had difficulty maintaining hot water in high demand situations.

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Appendix A – Draw Profiles

Table 11. Draw Profile 1 Details. Morning Segment Includes the Four Showers and the Evening Segment Contains Remaining Draws

Draw Profile 1				
Start time	**End Time**	**Flowrate (lit/min)**	**Liters/draw**	**Notes**
6:10	6:19	7.6	68.1	Shower 1
6:30	6:35	7.6	37.9	Shower 2
6:50	7:00	7.6	75.7	Shower 3
7:10	7:18	7.6	60.6	Shower 4
17:03	17:04	3.8	3.79	Food Preparation
17:04	17:05	1.9	3.79	
17:05	17:06	3.8	1.89	
17:09	17:10	3.8	3.79	
17:10	17:11	5.7	3.79	
17:12	17:14	3.8	5.68	
18:10	18:11	3.8	7.57	Hand Washing
18:11	18:12	1.9	3.79	
18:12	18:13	5.7	1.89	
18:13	18:14	3.8	5.68	
18:45	18:48	7.6	3.79	Dishwashing
18:55	18:57	7.6	22.71	
19:10	19:12	7.6	15.14	
19:50	19:54	11.4	15.14	Bath
20:50	20:51	1.9	45.42	Face Washing
20:51	20:52	3.8	1.89	
20:52	20:53	1.9	3.79	
20:54	20:55	3.8	1.89	

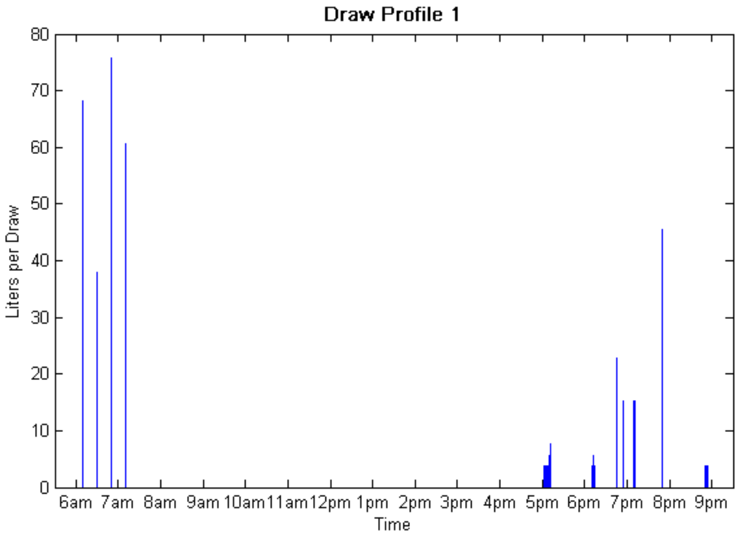

Figure 40. Graphical representation of Draw Profile 1

Table 12. Draw Profile 2 Details

Draw Profile 2			
Start Time	End Time	Flowrate (lit/min)	Liters/draw
6:00:00	6:00:30	3.8	1.893
6:10:00	6:10:30	3.8	1.893
6:20:00	6:21:00	3.8	3.785
6:35:00	6:35:30	3.8	1.893
6:50:00	6:50:30	3.8	1.893
7:05:00	7:06:00	3.8	3.785
7:10:00	7:11:00	3.8	3.785
7:55:00	7:55:30	3.8	1.893
8:05:00	8:05:30	3.8	1.893
8:20:00	8:20:30	3.8	1.893
8:35:00	8:35:30	3.8	1.893
8:45:00	8:45:30	3.8	1.893
8:50:00	8:50:30	3.8	1.893
9:05:00	9:05:30	3.8	1.893
9:10:00	9:10:30	3.8	1.893
9:15:00	9:15:30	3.8	1.893
9:25:00	9:26:00	3.8	3.785
9:30:00	9:31:00	3.8	3.785
9:35:00	9:36:00	3.8	3.785
9:40:00	9:41:00	3.8	3.785
10:50:00	10:51:00	3.8	3.785
10:55:00	10:56:00	3.8	3.785
11:00:00	11:00:30	3.8	1.893
11:05:00	11:05:30	3.8	1.893
11:30:00	11:31:00	3.8	3.785
11:35:00	11:36:00	3.8	3.785
11:40:00	11:41:00	3.8	3.785
11:45:00	11:45:30	3.8	1.893

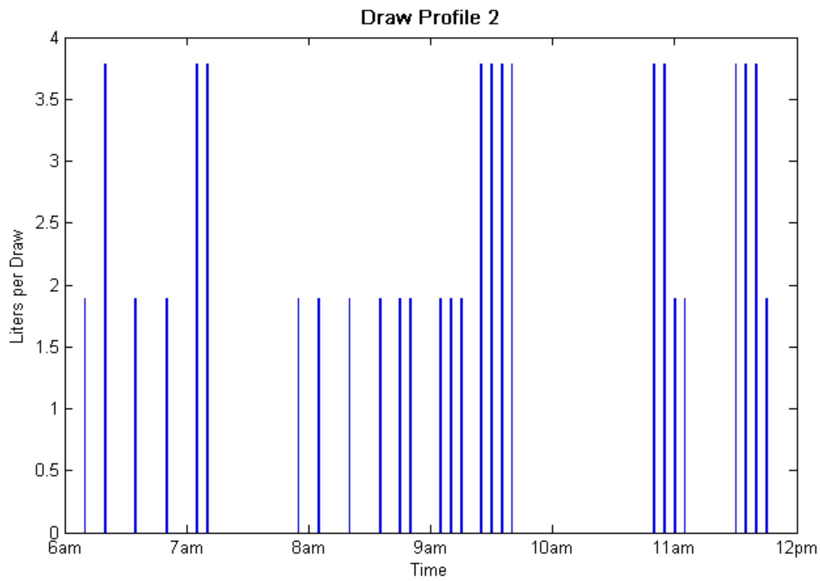

Figure 41. Graphical representation of Draw Profile 2

Appendix B – Laboratory Schematics

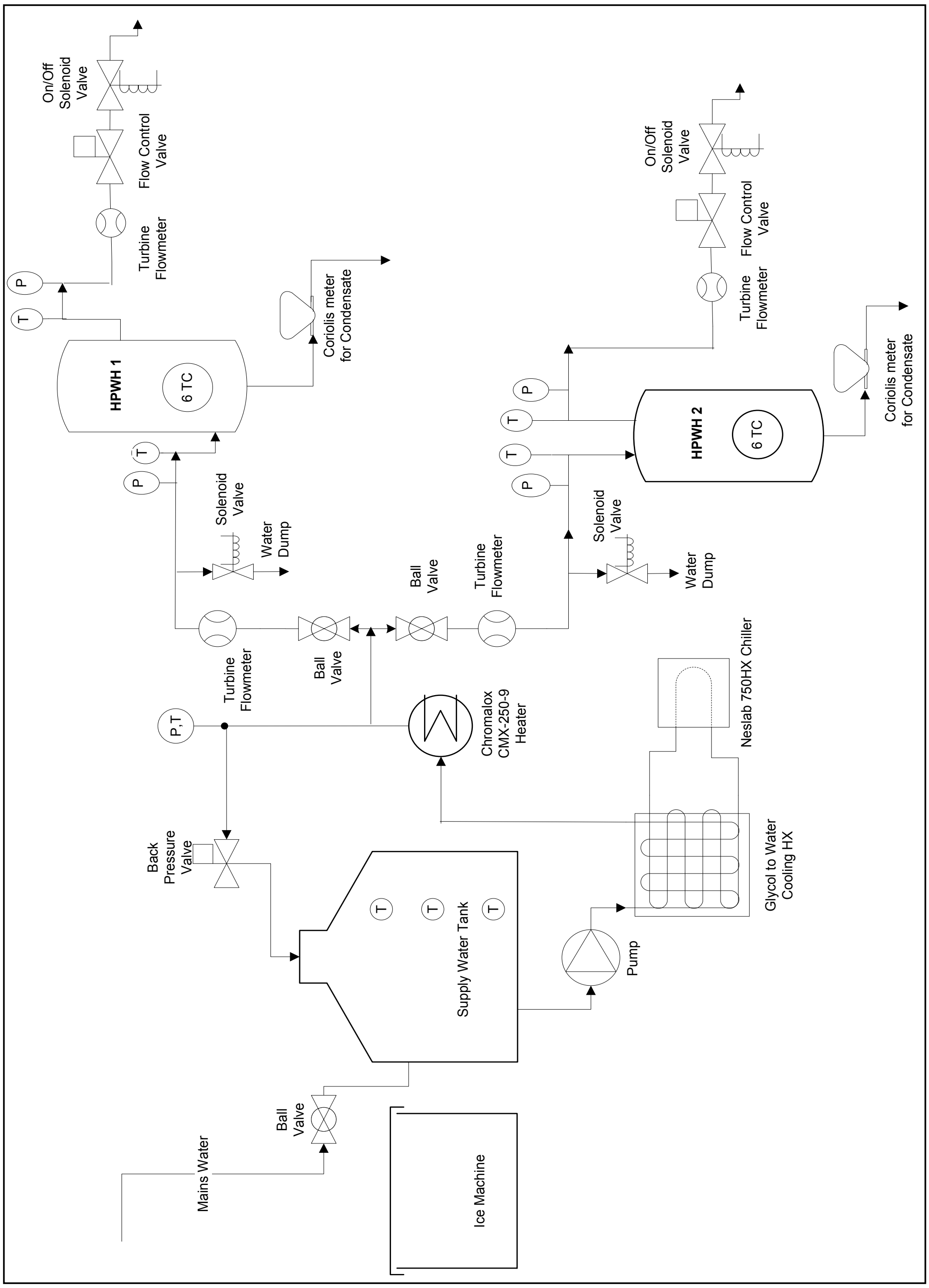

Figure 42. Water-side schematic

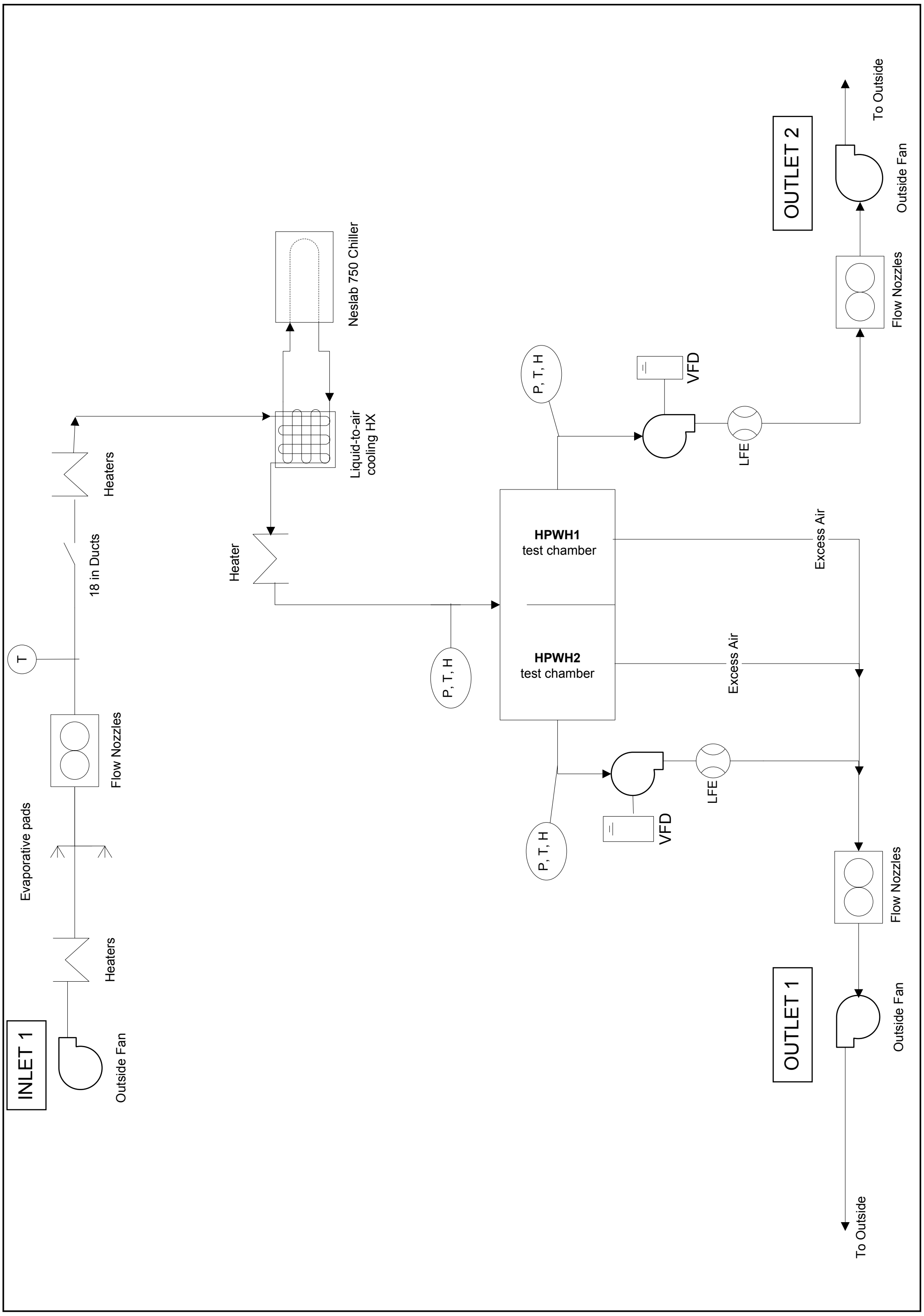

Figure 43. Air-side schematic

Appendix C – Heating Capacity Curves

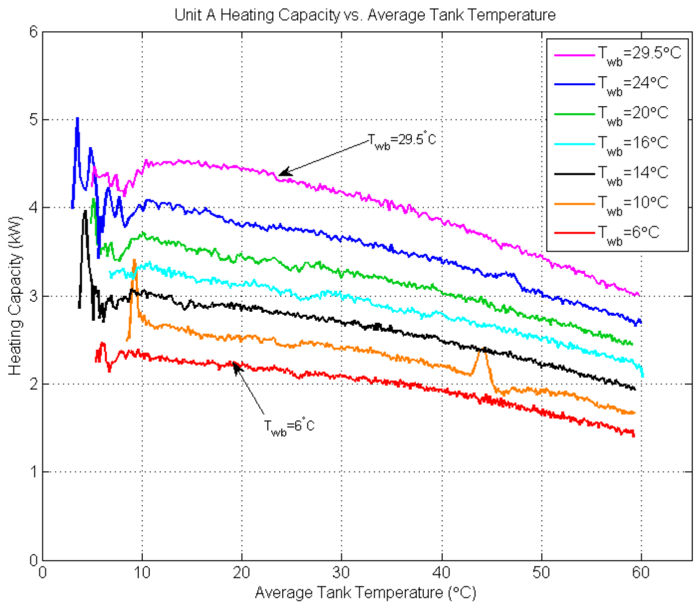

Figure 44. Heating capacity as a function of average tank temperature for Unit A

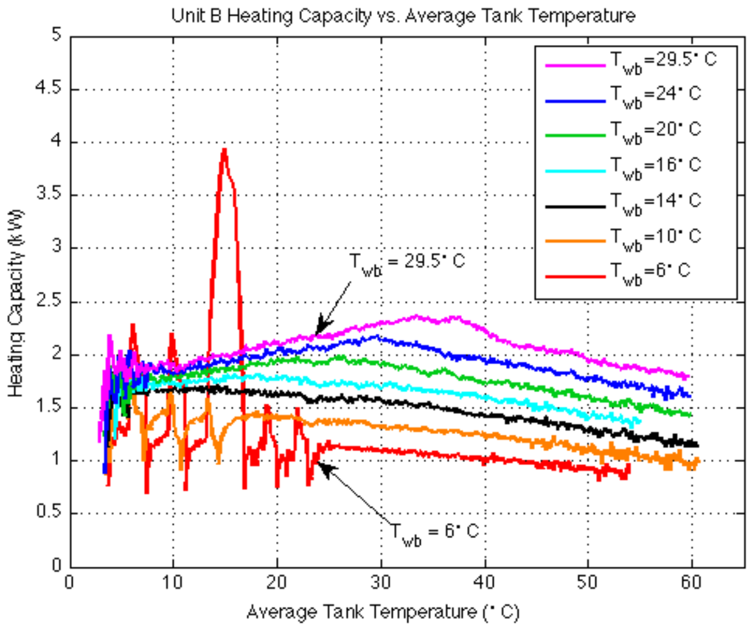

Figure 45. Heating capacity as a function of average tank temperature for Unit B

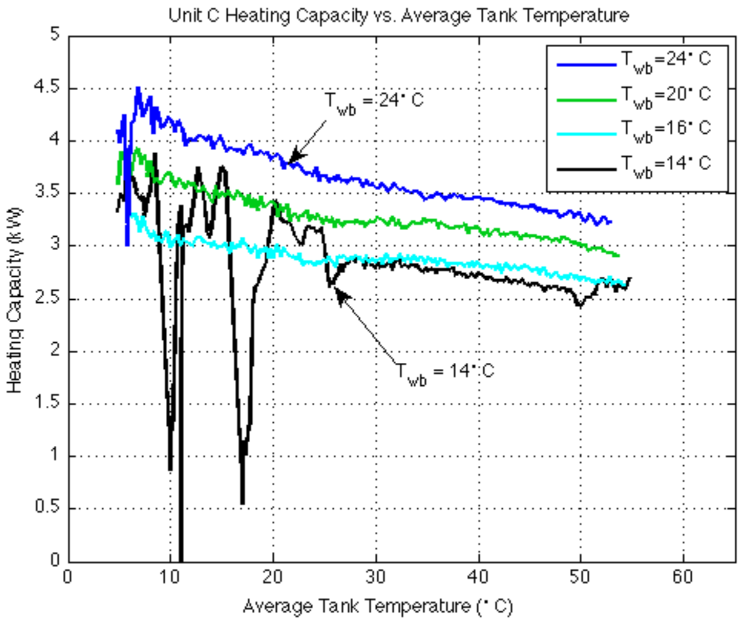

Figure 46. Heating capacity as a function of average tank temperature for Unit C

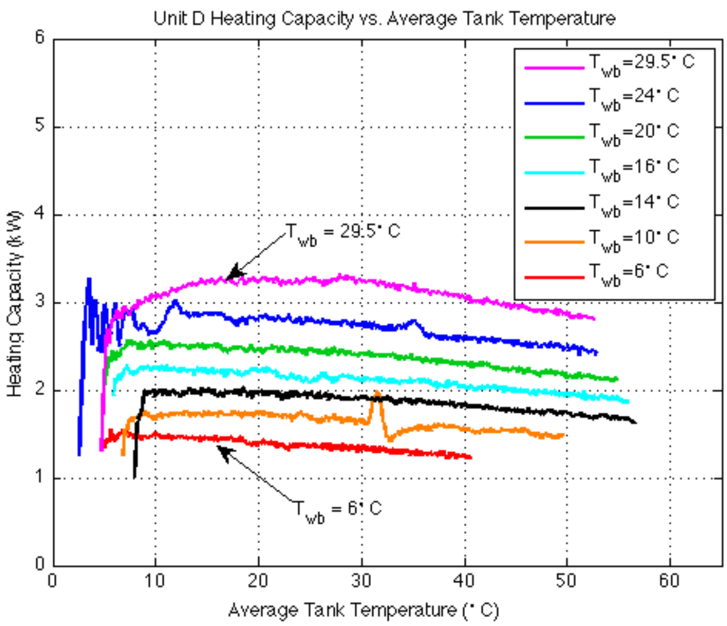

Figure 47. Heating capacity as a function of average tank temperature for Unit D

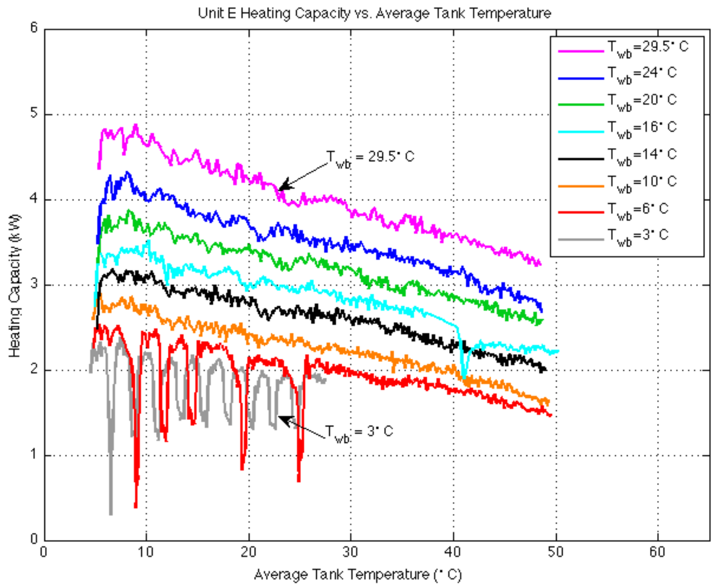

Figure 48. Heating capacity as a function of average tank temperature for Unit E