Technology Focus
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Field Testing of Pre-Production Prototype Residential Heat Pump Water Heaters

Introduction

The purpose of this *Technology Installation Review* is to provide an overview of the field testing of 18 pre-production prototype units of a “drop-in” type residential heat pump water heater installed in a wide variety of host home situations across the United States for more than one year. It provides descriptions of the construction, installation, control, instrumentation, and data acquisition methodologies employed with the units, as well as interpretations of the measured results.

In the United States, about half of all residential water heaters use resistance elements to heat the water inside a storage tank. Even the most efficient of these conventional units provides slightly less than one unit of useful energy (delivered to heat water) for each unit of electrical energy consumed. The best current conventional electric resistance unit has an energy factor of about 0.95 as determined according to the DOE Simulated Energy Use Test Procedure [Federal Register (1998)]. In contrast, by using electricity to “pump heat” from the surrounding air, a heat pump water heater can provide much more than one unit of useful energy for each unit of electrical energy consumed. With all losses included, the prototype heat pump water heater employed in this field test had an energy factor of about 2.4, according to the DOE test procedure.

Of course, the particular combination of hot water usage (amount and pattern), ambient air temperature, ambient air relative humidity, supply water temperature, and thermostat setting employed in the energy factor tests would not generally be the same as those encountered in any real home situation. Therefore, an important goal of these field tests, conducted by the Oak Ridge National Laboratory [Murphy and Tomlinson (2002)] under the sponsorship of the U.S. Department of Energy, was to measure the performance of the prototype heat pump water heaters operating in a wide range of real-world situations and to develop meaningful comparisons with the performance of conventional electric resistance storage water heaters operating in the same situations.

Technology Description

The heat pump water heater unit employed in the field tests described here was a pre-production prototype of a drop-in replacement for conventional residential electric water heaters (Fig. 1). The drop-in heat pump water heater has a footprint (22.25 in. diameter) common for conventional 50-gal water heaters and has the same requirements for power wiring (240-V, single-phase, 30-A circuit with ground) and for water connections (cold inlet from source to dip tube and hot outlet from tank to house). The temperature/pressure relief valve, the high-temperature cutout switch, and the upper and lower resistive elements are the same as in conventional electric water heaters.

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The main visual difference from a conventional unit is the addition of a small vapor compression heat pump system enclosed in a shroud on top of the tank. It increases the unit height to 60 in. and the unit weight to 180 lb. The heat pump uses a finned-tube refrigerant evaporator to remove heat from the ambient air induced by two fans through a rear grille with filter. It consists of four primary components—an evaporator, a compressor, a condenser, and an expansion valve—combined with connecting tubing, a refrigerant working fluid, and various controls.

In a heat pump cycle, heat is absorbed from the ambient air (in the evaporator, usually aided by fans) into a cold, low-pressure refrigerant liquid, thereby producing cool, low-pressure refrigerant vapor. The refrigerant vapor flows next to the compressor, where it is pressurized (with an associated temperature increase). From the compressor, the (now hot, high-pressure) vapor flows to the condenser, where it rejects heat to the water in the storage tank, thereby producing (warm, high-pressure) refrigerant liquid. The refrigerant liquid then flows to the expansion valve, which restricts the flow so as to produce a cold, low-pressure refrigerant liquid/vapor mixture at the exit of the valve. This mixture next flows to the evaporator to complete the cycle.

Heat is rejected from a refrigerant condenser comprising a copper-tubing coil wrapped securely around the outside of the bottom third of the water tank. The heat is transmitted through a highly conductive heat transfer mastic to the tank wall and thereby to the water. Polyurethane foam insulation was blown into the space between the tank wall and the unit's metal jacket to hold the condenser in place and to minimize heat loss from the tank. The total refrigerant charge of the unit used in the tests was 16 ounces of R-134a. Currently a drop-in heat pump water heater similar to the type tested is manufactured by ECR International.

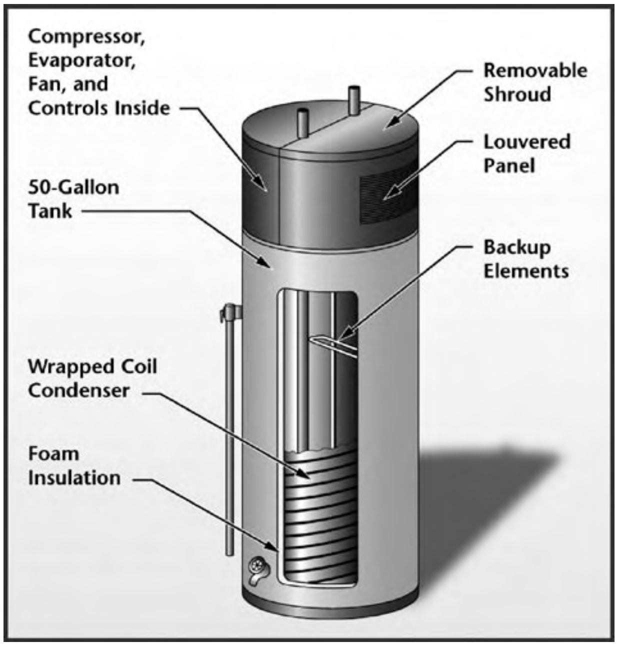

Figure 1. Sketch of heat pump water heater field test unit.

Control System

Each field unit employed a microprocessor-based control system. The microprocessor received and processed input from seven indicators (four thermistors, two switches, and one voltage divider) as enumerated in Table 1. All thermistors were sampled 32 times during each software cycle and averaged to minimize electrical noise distortions of temperature indications. Based on the processed values of the 7 inputs and on the values of the 16 adjustable control parameters stored in the electrically erasable programmable read-only memory (EEPROM), the control logic of the software determined which, if any, of five devices should be activated by means of associated relays. The controlled

Table 1. Inputs to the heat pump water heater control board

Input	Indicator
Thermostat setting	Voltage divider
Lower tank temperature	Thermistor
Upper tank temperature	Thermistor
Evaporator temperature	Thermistor
Compressor discharge temperature	Thermistor
Mode selection	Toggle switch
Condensate pan level (overflow)	Float switch

Table 2. Summary of unit installation situations

Unit	State	City	Residents	Water source	Unit location	Previous heater
1	Alabama	Douglas	2A	County	U. basement	Hybrid
3	Florida	Melbourne	2A, 1C	City	Garage	None
4	Alabama	Verbena	2A, 5C	County	C. laundry	80 gal
5	Florida	Milton	2A, 2C	City	Garage	50 gal
6	Tennessee	Knoxville	2A, 2C	City	Garage	80 gal
7	Connecticut	Cromwell	2A	City	S. basement	Hybrid
8	Washington	Seattle	2A, 2C	City	U. basement	52 gal
9	Connecticut	East Hampton	2A, 1C	Well	U. workshop	50 gal
10	Tennessee	Lenoir City	none	City	Closet	None
11	Florida	Pensacola	2A, 3C	City	Garage	50 gal
12	Oregon	Hillsboro	2A, 2C	Well	U. basement	80 gal
13	Georgia	Danielsville	2A, 2C	Well	S. utility	50 gal
14	North Carolina	Wake Forest	2A, 1C	City	U. workshop	50 gal
15	Oregon	Portland	2A	Well	Garage	50 gal
16	Georgia	Gainesville	2A, 3C	City	U. utility	50 gal
18	Georgia	Conyers	2A, 2C	City	U. basement	50 gal
19	Texas	Smithville	2A	County	C. laundry	50 gal
20	South Dakota	Madison	2A, 2C	City	C. basement	50 gal

C = conditioned, U = unconditioned, S = semi-conditioned

devices were the three heating devices (compressor, upper resistive element, and lower resistive element) and the two auxiliary devices (fan 1 and fan 2). To indicate which heating device was active, three colored light-emitting diodes were installed in a vertical column within the shroud so as to be visible through the evaporator air exit grille. When the upper resistive element was active, the top (green) diode was lit from the control board. The middle (yellow) diode indicated compressor activity and the bottom (red) diode indicated lower resistive element activity.

Control Logic

The control system logic incorporated hysteresis to avoid excessive equipment cycling and permitted only one heating device to operate at any one time. To minimize hot water runouts, the dominant heating device was set up to be the upper resistive element. Therefore, whenever the upper tank temperature fell below the thermostat setting minus the upper tank temperature hysteresis value, the upper resistive element was activated until the upper tank temperature exceeded the thermostat setting. If the upper tank temperature criterion was satisfied, lower tank heat was called for whenever the lower tank temperature fell below the thermostat setting minus the upper/lower tank temperature differential minus the lower tank hysteresis value. If lower tank heat was called for, the preferred device to activate was the compressor.

Fan operation was limited to periods when the compressor was active. If at any time after compressor startup the evaporator temperature fell below the fan 1 upper temperature limit minus the fan hysteresis value, fan 1 was activated until the evaporator temperature equaled or exceeded the fan 1 upper temperature limit. If, at any time after compressor startup, (with fan 1 already on) the evaporator temperature fell (additionally) below the fan 2 upper temperature limit minus the fan hysteresis value, fan 2 was activated until the evaporator temperature equaled or exceeded the fan 2 upper temperature limit. Thus compressor operation was accompanied, at various times, by no fan operation, fan 1 operation only, or fan 1 and fan 2 simultaneous operation.

If heat was called for in the lower section of the tank, but the compressor could not operate, the lower resistive element was activated. Once activated, the lower resistance element continued operation until:

1. the condition(s) preventing compressor operation were eliminated (causing compressor activation); (see discussion in Data Analysis section for description of some such conditions);
2. the lower tank temperature exceeded the thermostat setting minus the upper/lower tank temperature differential; or
3. the upper tank temperature fell below the thermostat setting minus the upper tank temperature hysteresis value (causing upper resistive element activation).

Field Demonstration

Test Site Characteristics

The cooperation of ten electric utilities was crucial in identifying potential host residences for the field test units, coordinating their installation, arranging for dedicated data acquisition telephone lines, and assisting with troubleshooting exercises. The testing benefited greatly from the wide range of situations made accessible by this cooperation and the willingness of the homeowners to participate.

As indicated in Table 2, 18 municipalities in 10 states, ranging from Connecticut to Washington to Texas to Florida, were represented among the test sites. Seventeen of the houses had two adults, and the number of children in the households ranged from none to five. The remaining house actually had no residents but served as a Habitat for Humanity construction office. In this case, scheduled hot water draws were accomplished by a solenoid valve activated by a timer. Four houses were served by well water and the remainder by central (city or county) water systems.

Six units were located in basements, of which one was conditioned (with direct access to the heating/ventilating/air-conditioning systems), four were unconditioned, and one was semi-conditioned. Five units were installed in (unconditioned) garages. Two units were sited in (conditioned) laundry rooms and two more in (unconditioned) workshops. An additional two units were installed in utility rooms (one unconditioned and one semi-conditioned). The unit in the Habitat house was installed in a small closet with two exterior walls, one interior wall, and one closed interior door. Two of the homes had no previous occupants and therefore no previous water heater. Ten residences had previously had conventional 50-gal resistance electric water heaters. Four of the homes had previously had larger-capacity conventional electric water heaters (three 80-gal, one 52-gal). Two of the residences had previously had add-on electric heat pump water heaters (from other manufacturers) in electric resistance hybrid arrangements of different capacities.

Field test project personnel were able to observe installation procedures at 13 of the sites and to verify initial proper performance of the field test units. The remaining five sites (Washington, Texas, South Dakota, and two in Oregon) were monitored during installation, and remote assistance was provided by field test project personnel as required. Upon installation, for safety reasons, the thermostat setpoint temperature was 120°F. However, residents were permitted to adjust this value as they saw fit throughout the test period by means of a knob on the front of each unit.

Testing Setup

Installation

Because of its integral design (heat pump and storage tank in a single, pre-assembled package), installation of the unit was truly "drop-in." That is, both the water and electrical connections were identical to those of a conventional electric resistance storage water heater. The only additional installation step was connection of a condensate drain line from the evaporator pan.

Data Acquisition

Strategy

Sensors were installed on each heat pump water heater to provide input to its associated data logger, which would preprocess and temporarily store the data in final storage. The data logger was connected to a modem that was connected to a dedicated phone line. To store data, on a regularly programmed weekly schedule, the central personal computer (with modem) called each data logger (through its associated modem) to download the data accumulated since the last download. To accomplish other functions related to installation, troubleshooting, or mode switching, manual calls using the personal computer were initiated to the relevant data logger.

Distinct strategies were employed to conserve data logger storage space, extend required download intervals, and minimize download time. First, the measurements were divided into three time-interval groups: "rapid" (every 2 seconds), "moderate" (every 30 seconds), and "slow" (every 10 minutes) so as to optimize the data streams required for performance assessment. Second, data transmittal to the final storage area of the data logger was programmed to be event-triggered. That is, data were transmitted from input storage to final storage only when hot water was being drawn (as indicated by the flow meter) and/or power was being drawn (as indicated by the total power transducer).

Instrumentation

Temperature, water flow, humidity, power, and condensate flow measurements were implemented with sensors on each heat pump water heater unit. The data logger, power supply, modem, power transducers, and pressure transducer were housed in a covered instrument box attached by aluminum brackets to the side of each unit.

Either an "open" (resistance mode) or a "closed" (heat pump mode) signal was sent from the control input/output channel on the logger to the mode switch input terminals of the heat pump water heater control board to set the desired operational mode. Successful implementation of this control strategy enabled both local and remote switching between operational modes. Remote mode switching was accomplished during phone connection to the data logger by manually changing the value of the associated flag in the custom data logger program.

Laboratory Checkout

Because the field test units were pre-production prototypes, and because some operational difficulties had been encountered previously with an earlier shipment of 10 units employed in durability tests [Baxter and Linkous (2002)], intensive checkout exercises were undertaken in the laboratory (Fig. 2) before shipment to the field test homes. Two tandem computer systems were used to monitor the performance of each unit during checkout, one for the installed instrumentation package (with communication through the data logger) and one for the heat pump water heater control system (with communication through the on-board microprocessor port). When necessary, changes to the EEPROM settings and control program were implemented through this second link.

With the monitoring systems in place, an extensive series of water heat-up and draw sequences was undertaken to exercise the various sensors and control systems. Anomalies were detected, causes identified, and solutions implemented until proper operation was verified. As was the case for the 10 durability tests, the most common problems were associated with unreliable splices in thermistor leads. Other detected anomalies were related to control board defects such as shorted mode switches, loose wiring, a failed light-emitting-diode connector, and a broken voltage regulator. In addition, two operational problems were found in the control program software. When all appropriate corrective measures had been completed, a final set of tests was conducted to verify correct remote communication and control operation using the central computer/modem/telephone line/modem/data logger system.

Data Processing

From the weekly downloads of data from the final storage of each logger, various algorithms were used to prepare weekly summaries. Specific calculated results from "rapid" data included hot water consumption, associated delivered heat value, source (inlet) water temperature, and maximum supply (outlet) water temperature. From "moderate" data, electricity consumption, compressor run time, upper resistive element run time, lower resistive element run time, beginning average tank temperature, and ending average tank temperature were calculated. These last two values were used to adjust the weekly hot water consumption values to account for additional heat stored in or removed from the tank. The effective weekly coefficient of performance (COP) was calculated (in nondimensional units) by dividing the net heat delivered to the hot water system by the electrical energy consumed.

Calculated values from "slow" data included ambient temperature range and run-time average, thermostat setting range, minimum evaporator temperature, and maximum compressor discharge temperature.

Data Analysis and Interpretation

Average weekly performance data taken from the 18 field test units during operation in the heat pump mode are presented in Table 3. The variations in volume of hot water consumed, useful energy delivered in that water, electrical energy consumption, and associated heating COPs for the systems illustrate the wide range of operating situations encountered at the field test sites.

Major Causes of Reduced Performance

A key factor that contributed to reduced COP performance in some units was a relatively large amount of resistive element (upper and/or lower) operating time. The primary reason for increased upper element operation was increased concentration (amount and time) of household hot water draws, particularly evident in units 8, 4, and 6. A less common cause was extended periods between draws. In this situation, average tank temperature slowly declined because of standby losses, and, over time, tank thermal stratification essentially disappeared as a result of thermal diffusion. As a result, the upper resistive element was activated by the falling upper tank temperature before the compressor or lower element

Table 3. Summary of average weekly heat pump water heater field test performance

Unit	Gal	kBtu	kWh	COP	% savings
13 (Danielsville, GA)	448	241	28.9	2.44	60
12 (Hillsboro, OR)	374	218	29.2	2.19	60
18 (Conyers, GA)	306	125	16.8	2.18	61
07 (Cromwell, CT)	270	135	18.4	2.15	58
20 (Madison, SD)	309	180	24.7	2.14	59
03 (Melbourne, FL)	499	197	27.1	2.13	59
11 (Pensacola, FL)	612	281	39.4	2.09	57
09 (East Hampton, CT)	511	310	44.3	2.05	56
16 (Gainesville, GA)	411	207	29.7	2.04	58
14 (Wake Forest, NC)	458	229	33.1	2.03	58
19 (Smithville, TX)	373	138	20.7	1.95	57
05 (Milton, FL)	451	219	33.8	1.90	53
01 (Douglas, AL)	444	228	35.6	1.88	52
04 (Verbena, AL)	794	388	60.8	1.87	50
06 (Knoxville, TN)	652	345	55.0	1.84	53
10 (Lenoir City, TN)	522	226	40.9	1.62	44
08 (Seattle, WA)	805	423	80.8	1.53	40
15 (Portland, OR)	95	56	16.4	1.00	45
Simple averages	463	230	35.3	1.95	54

was activated by the drop in lower tank temperature. This condition was most frequently encountered in unit 15. Also for this unit, extremely low heat demand magnified the detrimental effects of given standby losses.

Increased lower resistive element operating time was caused by conditions that kept the control system from allowing compressor operation. In the case of unit 10, the substantial cooling of air in the small closet (especially during cold weather) caused the evaporator temperature to reach its lower limit, shutting down the compressor and activating the lower resistive element. In the case of unit 8, concentrated hot water draws combined with low inlet water temperature and low ambient temperature (during cold weather periods) prevented the compressor discharge temperature from reaching the required value in the allowed time, shutting down the compressor and activating the lower element. Less frequent causes of lower element activation were excessive compressor discharge temperatures (especially in high ambient and high thermostat setpoint temperature situations) and on/off compressor timer violations.

Mode Comparisons

Figure 2 illustrates daily hot water consumption for one week of unit 9 operation in the resistance mode. It is clear from these data that the heaviest usage occurred during the two weekend days. In Fig. 3, the dramatic variation of hourly hot water consumption for Saturday of that week is demonstrated. This pattern of variation is followed closely by the hourly electricity consumption given in Fig. 4. Data from the same unit operating in heat pump mode two weeks later show a similarly uneven pattern of hot water usage in Fig. 5. However, the corresponding electricity consumption data presented in Fig. 6 show a decidedly more uniform demand pattern, with consistent, low power draws (from the compressor and fans). Table 4 presents the measured performance during one week of operation in each mode for this unit and the calculated electricity savings (about 61% in this case) for the heat pump mode relative to the resistance mode.

A limited amount of resistance mode data was acquired from 16 of the field test units. As expected, most of the heating by far in this conventional mode was accomplished by the lower resistive element. Of course, the size of the deviation in COP from unity in this case was an indication of the relative size of standby losses characteristic of each location, as mentioned earlier.
The average weekly data for heat pump and resistance modes are plotted as electrical energy consumption versus delivered heat energy in Fig. 7. For any given amount of delivered heat energy, the energy savings that could be achieved by the use of heat pump mode compared with resistance (conventional) mode can be directly estimated as the vertical distance between data for the two modes. Based on this data, unit-by-unit estimates of percentages of electrical energy savings were calculated. The results, presented in Table 3, ranged from 40 to 61%.

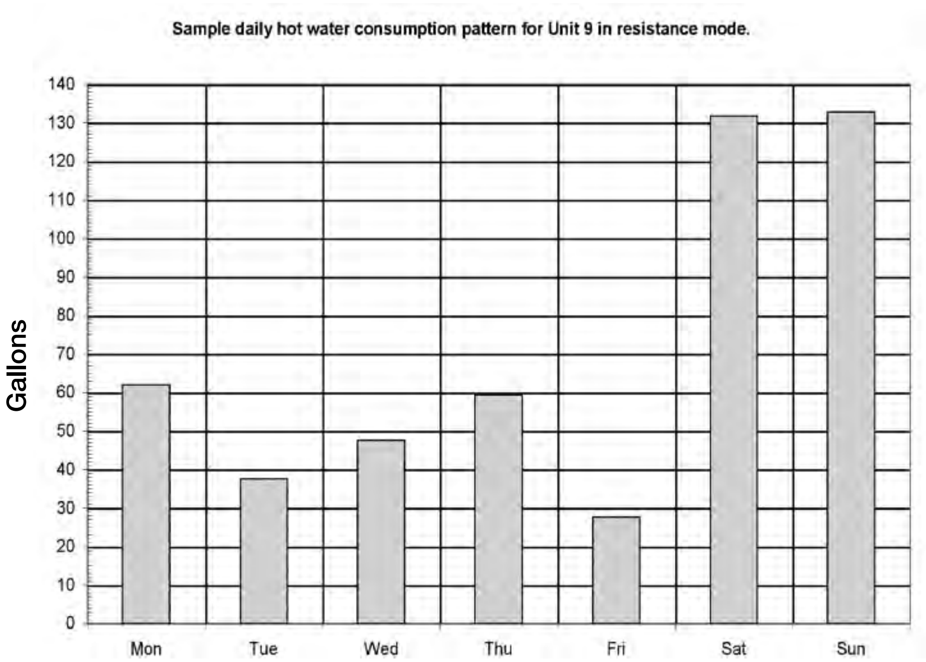

Figure 2. Sample daily hot water consumption for Unit 9 in resistance mode.

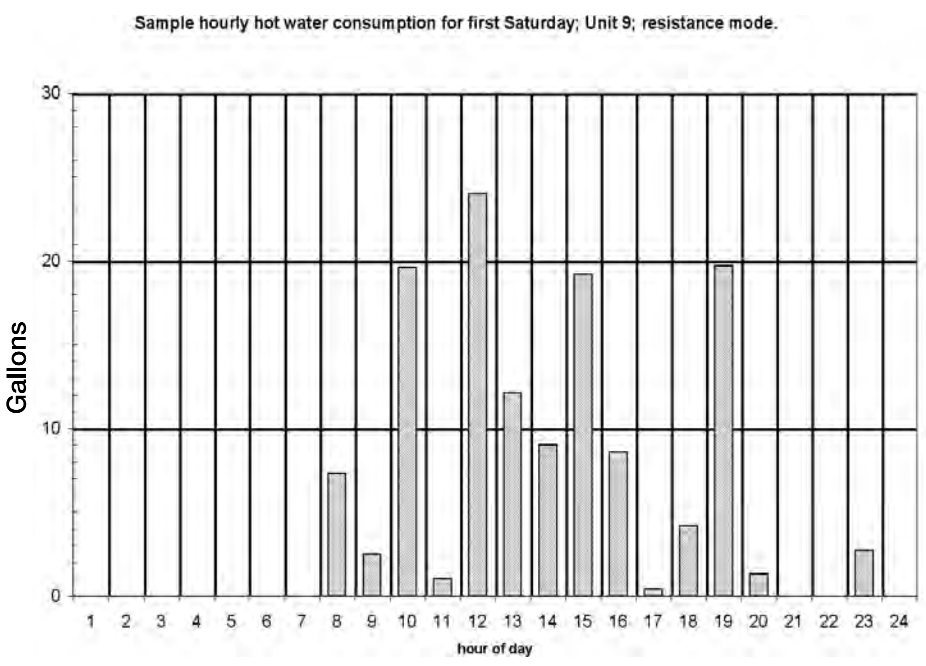

Figure 3. Sample hourly hot water consumption for first Saturday; Unit 9; resistance mode.

Electrical Demand Comparisons

Summer electrical demand data were broken down into 15-min intervals and aggregated for six units operating over a 6-week period in the resistance mode to produce day-by-day profiles [Tomlinson and Murphy (2004)]. The relatively consistent weekday patterns were then averaged to produce the characteristic "double-humped" weekday profile given in Fig. 8. The same methods were used to generate the analogous profile for the same six units operating in heat pump mode. This profile, also presented in Fig. 8, had a generally smaller amplitude than the corresponding resistance mode profile, reflecting the higher COPs associated with the heat pump mode. Winter data from the same units and modes were analyzed in the same manner to provide the results shown in Fig. 9. In this case, the heat pump mode profile had a much smaller amplitude than the resistance mode profile over virtually the entire average weekday. The striking exception was during the very early morning hours, when, in heat pump mode, the compressor and fans continued to run to complete recharging of the hot water in the tank. As can be seen from a comparison of Figs. 8 and 9, the winter data profile for each mode had the same general shape, but exhibited a larger amplitude, when compared with the summer case. This trend was expected as the result of greater demand for delivered hot water heat and possibly reduced efficiency during cold weather.

Several primary factors can contribute to greater demand in the winter period. Lower inlet water temperature (except, possibly, where the source is a deep well) means that more heat is required to raise the water temperature the thermostat setpoint temperature. With lower inlet water temperature, cold water/hot water mixing applications (for showers, etc.) will require a greater proportion of hot water and/or a higher thermostat setting to deliver water at a given temperature. If hot water pipes are exposed to lower ambient temperatures, more heat is lost to the surroundings as the hot water travels through them, also requiring greater hot water flow (or longer pre-run

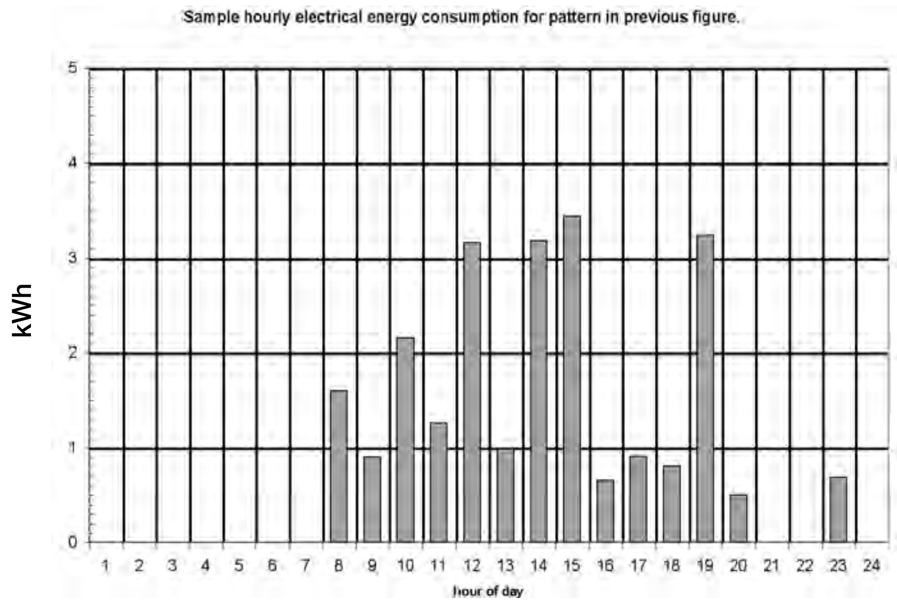

Figure 4. Sample hourly electrical energy consumption for pattern in previous figure.

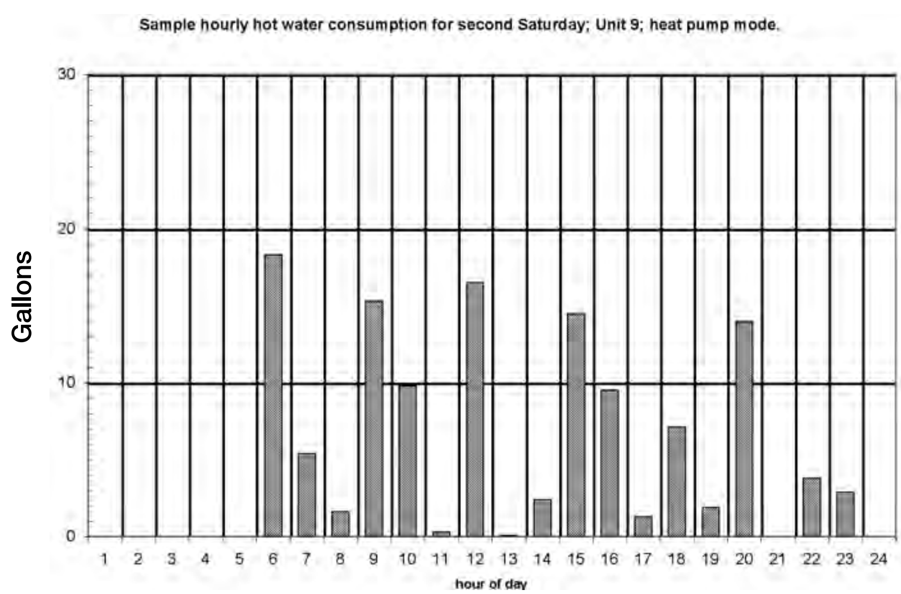

Figure 5. Sample hourly hot water consumption for second Saturday; Unit 9; heat pump mode.

intervals to bring delivery temperature up to the desired level) and/or a higher thermostat setting to deliver water at the desired temperature. If the ambient temperature decreases and/or the thermostat setpoint temperature increases, standby losses associated with conduction also increase. Occupants may also take longer showers and baths to warm up from exposure to cooler surroundings.

Seasonal Effects of Ambient Temperature and Supply Water Temperature

Even with seasonal variations in demand, seasonal variations in COP were expected to be smaller in field situations where both the ambient temperature and the supply water temperature were generally constant throughout the year. Unit 13 was installed in a conditioned utility room (with relatively small fluctuations in ambient temperature) and was supplied by well water (characterized by relatively small fluctuations in supply water temperature). Weekly values of minimum evaporator temperature, average ambient air temperature, and normalized (to average) COP acquired over 75 weeks are shown in Fig. 10. Periods with incomplete or atypical data (e.g., vacations) were not included.

The data for the ambient air temperature measured near the heat pump water heater vary between 64 and 72°F during this period. The measured evaporator temperature data generally follow the same pattern, varying between 44 and 54°F during the same period. Of course, the evaporator temperature is displaced considerably (approximately 19°F) below the ambient air temperature to accommodate the required heat transfer from the ambient air to the evaporator. The corresponding normalized COP data in the same figure show relatively small fluctuations (from 9% below to 10% above the average) during the same period.

Unit 14 was installed in an unconditioned garage and was supplied by a city water system. This situation subjected the heat pump water heater to substantial seasonal fluctuations in both the ambient temperature and the supply water temperature. The corresponding weekly averages acquired over a period of 104 weeks are shown in Fig. 11. In contrast to Fig. 10, significant seasonal variations are evident. The weekly average ambient air temperatures measured near the heat pump water heater range from 37 to 82°F during this period. Minimum evaporator temperature data follow a similar pattern, varying between 27 and 58°F during the same period. The normalized COPs also show relatively large fluctuations (from 38% below to 28% above the average). Each of the three parameters is in phase (that is, low COP coincides with low ambient temperatures and low evaporator temperatures), and they show cyclic variations closely correlated with the change in seasons and in outdoor average air temperatures. The average COP for this unit was lower than that for unit 13 for several reasons:

1. the overall average ambient temperature and minimum evaporator temperature for unit 14 were lower (see discussion below);
2. the water use pattern for the unit 14 family included more heavy hot water use instances than the pattern for the other family (causing more usage of the upper resistive element); and
3. the thermostat was set somewhat higher by the unit 14 family than by the unit 13 family (resulting in higher condenser temperature operation for unit 14).

It should be noted that, for unit 14, the displacement of the evaporator temperature below the ambient air temperature varied from 27°F at higher air temperatures to 9°F at lower air

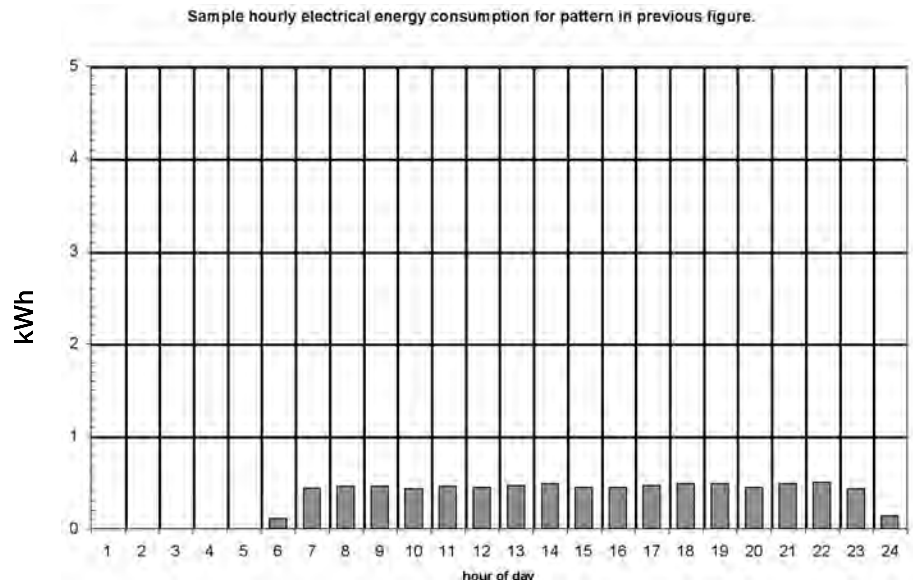

Figure 6. Sample hourly electrical energy consumption for pattern in previous figure.

	Heat pump mode (01/01 01/07)	Resistance mode 12/18 12/24)	Resistance mode (adjusted)
Heat energy delivered (kBtu)	285	272	285
Electrical energy consumed (kWh)	36.5	89.9	94.2
Heating coefficient of performance	2.29	0.89	0.89
Savings using heat pump mode	94.2 –36.5 57.7 kWh (61.3%)		

Table 4. One-week measured heat pump mode/resistance mode performance/savings comparison for unit 9

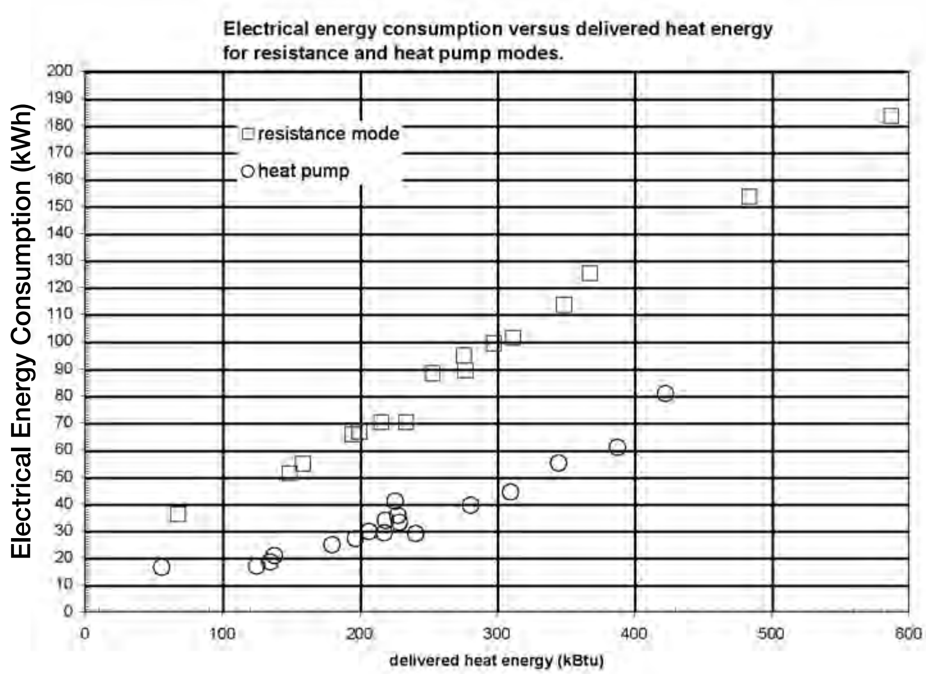

Figure 7. Electrical energy consumption versus delivered heat energy for resistance and heat

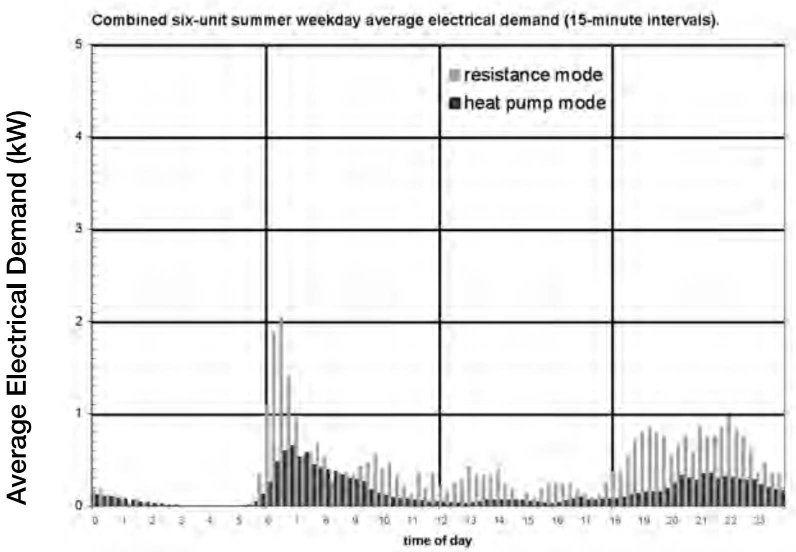

Figure 8. Combined six-unit summer weekday average electrical demand (15-minute intervals).

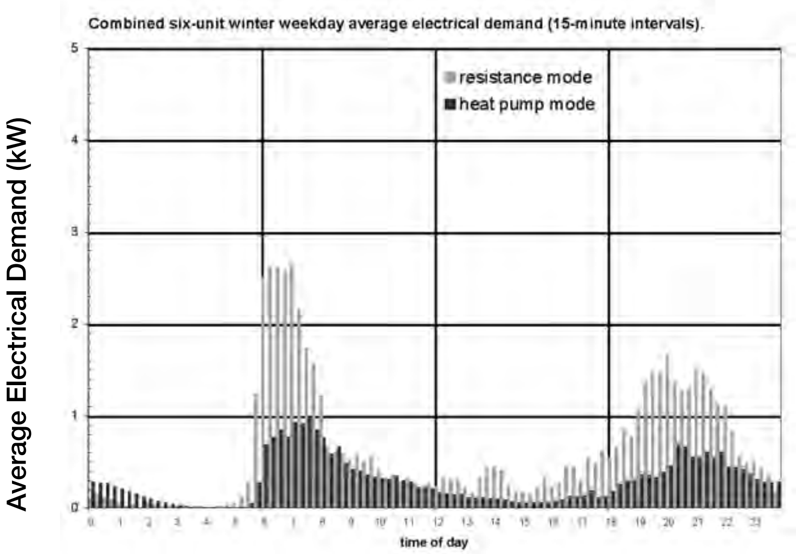

Figure 9. Combined six-unit winter weekday average electrical demand (15-minute intervals).

temperatures. This reduced difference in heat transfer temperature reflects the reduced capacity of the heat pump system to remove heat from the air at low ambient air temperatures. Although the heat pump's power requirement also drops at low ambient air temperatures because of reduced compressor load, the normalized COP data show that the reduction in heat removal capacity is greater than the power reduction.

Another characteristic of the normalized COP data for unit 14 in Fig. 11 is that the depth of the "valleys" at low ambient temperatures is greater than the height of the "peaks" at high ambient temperatures, compared with the average. In fact, the extremes of the valleys coincide with the lowest ambient air and evaporator temperatures seen. In these situations, to prevent frost buildup on the evaporator coil, the heat pump water heater controls automatically terminated heat pump operation (compressor and fans) and activated the lower resistance element. The resulting electric resistance heat operation substantially reduced the weekly average COP below that achievable with the heat pump system alone (if frost were not a problem).

Summary of Results

Eighteen pre-production prototype drop-in residential heat pump water heaters were instrumented, pre-tested for operational problems in a laboratory environment, installed in a wide variety of host homes across the United States, and monitored for more than one year to determine performance and energy savings. Each 50-gal integral unit, incorporating a heat pump system with a storage tank in a single, pre-assembled package, served as a drop-in replacement for a conventional electric resistance storage water heater. Results of the testing indicated that performance was sensitive to hot water usage (amount and pattern), ambient temperature, inlet water temperature, and thermostat setting.

Measured energy savings ranged from 40 to 61% compared with an efficient conventional electric resistance storage water heater. Aggregate demand peaks were also found to decrease substantially compared to conventional units.

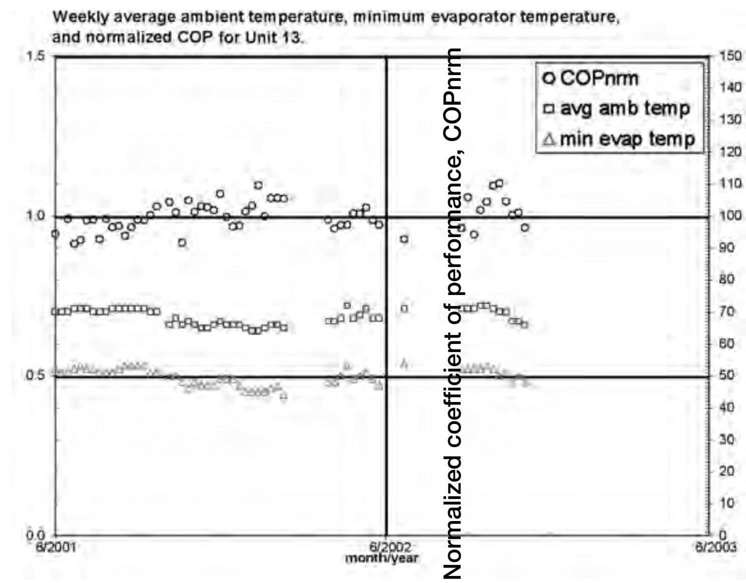

Figure 10. Weekly average ambient temperature, minimum evaporator temperature,

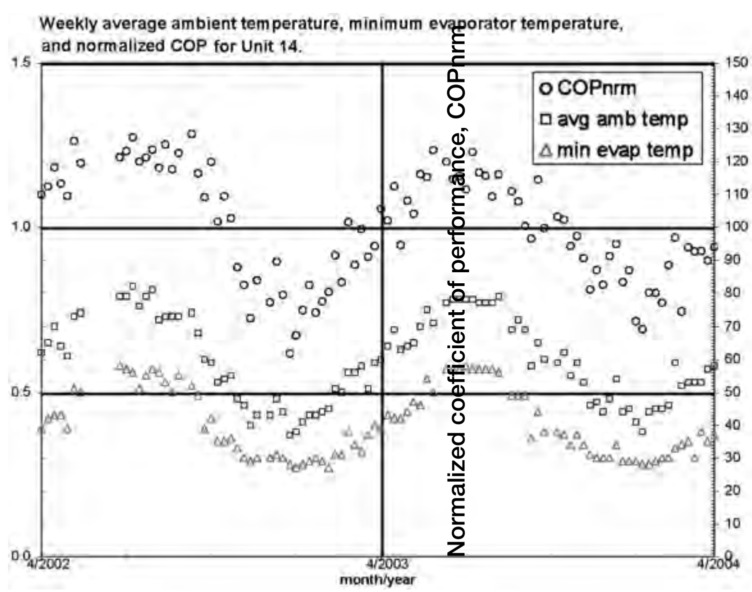

Figure 11. Weekly average ambient temperature, minimum evaporator temperature, and normalized COP for Unit 14.

Anticipated Commercialization

Two firms that manufacture a large share of the water heaters sold in North America have formed teams to develop designs for heat pump water heaters. These water heaters are expected to appear on the market in the near future at a price yielding paybacks no longer than three years, which would make them very attractive for any application.

This technology offers the promise of significant reductions in energy usage and peak demand, which should be of interest both to electric utilities and their customers. The HPWH will be useful in any type of housing, and especially if installed in large numbers, such as in military family housing or public housing, can contribute significantly to reducing energy costs and meeting federal energy goals.

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