# RESIDENTIAL HEAT PUMP WATER HEATER (HPWH) DEVELOPMENT STATUS - USA

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## ABSTRACT

Heat pump water heaters (HPWH) have the potential to reduce annual water heating costs for residential and commercial buildings by a factor of 2 or more compared to conventional electric resistance water heating products. This paper summarizes the current state of HPWH development in the United States including design evolution, laboratory performance, field performance, and accelerated life test results. Also discussed are consumer perceptions of current products and an assessment of factors impacting market acceptance of HPWHs. The laboratory and field studies indicate that the technology has progressed considerably with fairly reliable and highly efficient products becoming available. However, market penetration remains small to-date, primarily due to high initial costs.

## 1 INTRODUCTION

Water heating accounts for about 4% of all the energy used in the USA and 10% of all energy used in buildings - a total of about 4.0 exajoules (DOE/EERE 2004). Consequently, improving the efficiency of water heating can play a significant role in reducing the nation's thirst for energy. The efficiency of electric resistance water heaters (EWH) has just about topped out, and the efficiency market is tightly compressed. US efficiency standards require EWHs to have a minimum Energy Factor (EF, standard water heater efficiency metric) of 0.90, and the most efficient models have EFs of about 0.94 to 0.95. There is simply not much room left for further improvement in EWH efficiency. The heat pump water heater (HPWH) however can overcome this limitation and increase electric water heating efficiency by a factor of two or more. HPWHs employ a vapor compression refrigeration cycle to transfer heat from ambient air into the water. Potential additional useful outputs of a HPWH, depending upon its location within a building, include space cooling and dehumidification.

There are two basic designs of electric HPWHs – add-on and integral. The "add-on" type contains a compressor, evaporator, controls, and a water-cooled condenser and is installed in conjunction with an existing EWH. This type includes a small pump to circulate water from the EWH tank to the HPWH. Piping must be installed between the EWH and HPWH, and the HPWH generally replaces the function of the lower electric resistance element in the EWH. An advantage of the "add-on" type is that it is retrofittable and can be installed by the end user. Figure 1 is a picture of a new prototype add-on HPWH developed in 2002 by a small US manufacturer. The relatively compact package is about 317.5 mm wide, 419 mm high, and 533.4 mm deep. Water connections on the back of the package are piped to a storage EWH tank via a coaxial fitting installed in the bottom of the tank where the tank drain valve is normally located. Water is circulated from the storage tank to the HPWH condenser and back though this fitting as illustrated in Figure 2. The unit is designed for ease of installation by a "do-it-yourself" homeowner or a plumbing contractor and is equipped with a grounded plug for connection to a typical 115-V house outlet.

**Figure 1** Add-on HPWH package.

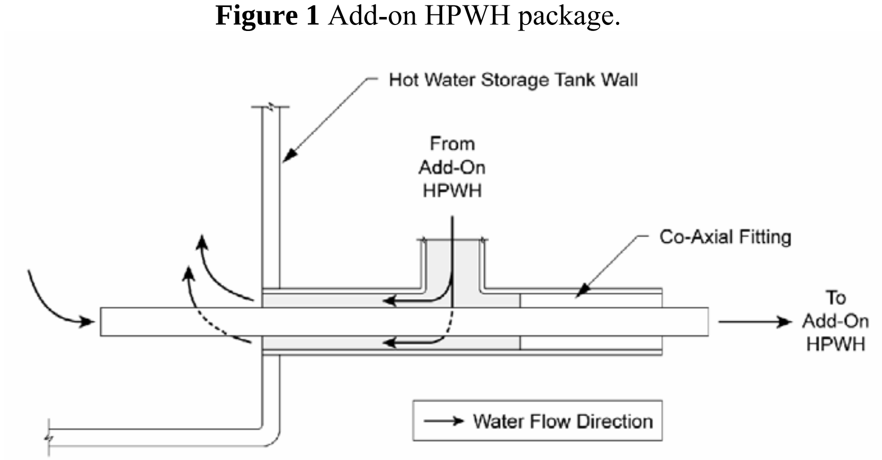


**Figure 2** Schematic of tank water fitting used with add-on HPWH unit.

The "integral" type is a single package containing the HPWH components, controls, and storage tank. A "drop-in" version of the integral HPWH, shown in cutaway view in Figure 3, has been developed. This design is intended to target the large replacement market for residential EWHs. In this context "drop-in" means that it can be installed with about the same effort and in the same location as the EWH it would replace. Actual experience in with 20 units California indicates that installation on average took about 1-2 hours longer than for an EWH (CEC 2004). Major reasons involve the increased weight over EWHs and the time to install a condensate drain line for the evaporator. Increased experience should lead to reductions in this incremental installation time.

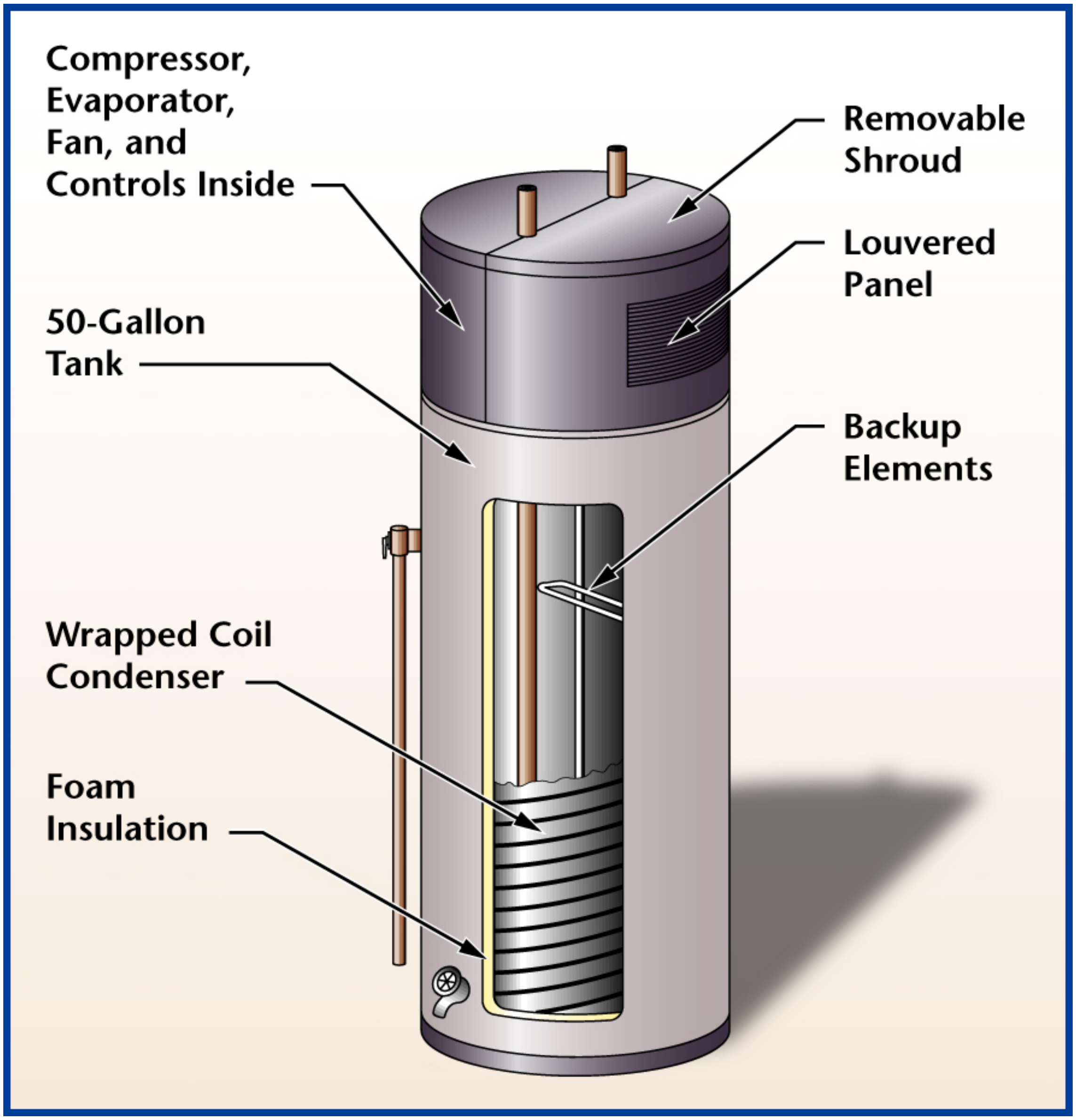


**Figure 3** Cutaway schematic view of the "drop-in" HPWH.

Development of the "drop-in" design was a collaborative effort between Arthur D. Little, Inc. (ADL), EnviroMaster International (EMI; subsidiary of ECR International), and Oak Ridge National Laboratory (ORNL) with sponsorship from the Department of Energy (DOE), the New York State Energy Research and Development Authority (NYSERDA), and the California Energy Commission (CEC). The design is based on a patented concept originally developed in the late 1990's (US Patents 1999a, 1999b). A prototype production design was developed based on the patented concept in 1999. This design was subsequently refined and ultimately achieved an energy factor (EF) rating per the DOE Simulated Use Test procedure (Federal Register 1998) of 2.47 in early 2000 (Tomlinson, 2000).

## 2 TECHNOLOGY DEVELOPMENT STATUS

Ten of the prototype "drop-in" HPWHs were delivered to ORNL in late summer of 2000 for a durability test program (Baxter and Linkous 2002). In addition eighteen units were built and sent to

ORNL for a DOE national field test program (Murphy and Tomlinson 2002), and another 20 built for a field test program in California (CEC 2004).

### 2.1 Durability Testing

The durability testing consisted of running the HPWHs through about 7300 water heat cycles over a 9-10 month period to represent about 10 years of normal operation in a residence. All ten units were placed in an environmental chamber and subjected to a set of representative ambient conditions that grew progressively harsher with time and number of cycles (Table 1). The goal was to identify design and component weaknesses that could impact the reliability and performance of the HPWH over 10 years of simulated residential use. The testing protocol and test facility along with detailed results are described by Baxter and Linkous (2002) and briefly summarized herein.

**Table 1** Operating conditions for each stage of durability test protocol

| Stage | Cycles | Ambient air conditions | HPWH power supply voltage |
|---|---|---|---|
| 1 | 2000 | 24-27 °C dry bulb temperature<br>50% relative humidity | Normal |
| 2 | 2000 | 24-27 °C dry bulb temperature<br>80% relative humidity | Normal |
| 3 | 2000 | 38 °C dry bulb temperature<br>50% relative humidity | Normal |
| 4 | 1200 | 38 °C dry bulb temperature<br>50% relative humidity | 15% reduced voltage |
| 5 | 100 | 20 °C dry bulb temperature<br>50% relative humidity | Normal |

There were no failures of any of the major mechanical components on the HPWHs over the course of the test period. Most of the problems experienced involved the control system temperature input sensors. Sixteen of the sensors out of 40 (total for all ten HPWHs) failed for a 40% failure rate. These sensors were thermistors that had very fine lead wires and included a spliced connection to provide connecting leads from the thermistor location to the control board terminal points. All of the thermistor failures were due to failures of these splices either as shorts or open circuits. One unit experienced failures of two control boards and several units had problems with thermostats and control boards coming loose from their mountings and one thermostat failure occurred. In addition the controls on all ten test units experienced occasional erratic behavior caused by random electronic noise spikes in the low voltage control circuitry. The source of the noise problem is not known with complete certainty but is felt to be due in large part to the fact that the low voltage sensor wires were bundled with the high voltage power wiring for the heat pump and backup electric heating elements.

Both the tanks and compressors were subjected to tear down and examination after the durability test run. No excessive or unusual wear was noted on any of the tanks. The compressors were also in very good shape but there was a consistent wear pattern noted on the crankpin bushing on all of the units. Discussions with the compressor manufacturer indicated that this wear pattern was probably due to heavy loading associated with excessive compressor discharge temperatures (>115.5 ºC) experienced during the testing.

### 2.2 Field Tests

Eighteen of the HPWHs were instrumented, pre-tested in a laboratory environment, installed in a wide variety of occupied host homes across the United States, and monitored to determine performance over 1-2 years (Murphy and Tomlinson 2002). These test units were remotely controlled to operate in both HPWH and conventional EWH modes to facilitate measurement of HPWH energy savings and peak kW reductions versus the EWH baseline. Table 2 gives summary results from the field tests. Measured energy usage averaged about 55% less for the heat pump water heater than for a conventional resistance water heater.

**Table 2** "Drop-in" HPWH field test results listed in order of energy cost savings

| Test site | Location in house[1] | Electricity cost (¢/kWh) | Water use[2] | Energy use (kWh/wk) | COP | Savings vs. resistance (kWh/wk) | Savings vs. resistance % | Energy cost savings ($/wk) |
|---|---|---|---|---|---|---|---|---|
| E. Hampton, CT | N | 9.64 | 1.14 | 44.3 | 2.05 | 56.7 | 56.1 | 5.46 |
| Seattle, WA | N | 8.65 | 1.73 | 74.3 | 1.57 | 52.2 | 41.3 | 4.51 |
| Wake Forest, NC | N | 8.98 | 1.01 | 33.5 | 2.02 | 46.1 | 57.9 | 4.14 |
| Knoxville, TN | N | 5.81 | 1.44 | 55.2 | 1.84 | 62.7 | 53.2 | 3.64 |
| Pensacola, FL | N | 6.40 | 1.36 | 39.2 | 2.09 | 51.0 | 56.5 | 3.26 |
| Hillsboro, OR | N | 7.29 | 0.83 | 29.2 | 2.18 | 43.8 | 60.0 | 3.19 |
| Verbena, AL | C | 5.29 | 1.76 | 60.8 | 1.87 | 60.2 | 49.7 | 3.18 |
| Gainesville, GA | N | 6.89 | 0.91 | 30.4 | 2.02 | 43.8 | 59.0 | 3.01 |
| Danielsville, GA | C | 6.89 | 0.96 | 28.2 | 2.44 | 43.5 | 60.7 | 3.00 |
| Melbourne, FL | N | 7.00 | 1.11 | 23.8 | 2.21 | 38.8 | 62.0 | 2.72 |
| Cromwell, CT | SC | 9.64 | 0.60 | 18.4 | 2.15 | 25.6 | 58.1 | 2.46 |
| Milton, FL | N | 6.40 | 1.00 | 33.2 | 1.91 | 37.1 | 52.8 | 2.38 |
| Douglas, AL | N | 5.90 | 0.98 | 35.7 | 1.87 | 38.5 | 51.9 | 2.27 |
| Smithville, TX | C | 7.00 | 0.83 | 22.0 | 1.97 | 29.6 | 57.4 | 2.07 |
| Portland, OR | N | 7.25 | 0.36 | 24.1 | 1.18 | 28.5 | 54.0 | 2.07 |
| Lenoir City, TN | SC | 5.81 | 1.12 | 39.1 | 1.64 | 32.2 | 45.2 | 1.87 |
| Conyers, GA | N | 6.89 | 0.68 | 17.1 | 2.16 | 26.9 | 61.1 | 1.85 |
| Madison, SD | C | 4.84 | 0.69 | 24.7 | 2.14 | 35.9 | 59.3 | 1.74 |
| Simple averages | | 7.03 | 1.03 | 35.1 | 1.96 | 41.9 | 55.3 | 2.93 |

[1]Space characteristic: N = non-conditioned; SC = semi-conditioned; C = fully conditioned

[2]Normalized to 0.243 $m^3$/d or 1.70 $m^3$/wk – water use rate for US standard water heater performance rating procedure (Federal Register 1998)

Results indicated that performance was sensitive to hot water usage (amount and pattern), ambient temperature, supply water temperature, and thermostat setting. Weekly average energy savings ranged from 62% for a unit located in a garage in Melbourne, FL (moderate water use and high delivery COP) to 41% for a unit located in a basement in Seattle, WA (high water use and low delivery COP). The Seattle unit used much more electric resistance back up heat than the others for several reasons: 1) a large fraction of its weekly water use was concentrated in a relatively short time during the mornings (four people taking showers at once), 2) cold water supply temperature (~ 7 ºC), and 3) cool ambient air temperature (~ 9 ºC) in the unconditioned basement where the HPWH was located. These factors reduced the ability of the compressor alone to meet the hot water demand resulting in a low overall delivery COP. Interestingly, water heating cost savings does not necessarily correspond directly to overall efficiency. The high total water use at the Seattle location together with the relatively high electricity cost resulted in the second-highest weekly cost savings of all the units despite the having the second lowest low overall COP.

Diversified peak kW demand for a subset of six of the field test units was determined. Figures 4 and 5 illustrate the 15-minute kW demand for both HPWH and EWH modes for winter and summer, respectively. The graphs show a characteristic double peak for both modes, one in the morning and another in the evening. The HPWH mode 15-minute diversified demand was up to 1.9 kW lower than that of the EWH mode during winter morning peak periods (6-8 am). Peak reduction during summer afternoons (1-7 pm) was up to 0.6 kW compared to the EWH baseline.

Hot water deficits (loss of hot water during use) and cooling/dehumidification performance for the HPWH was studied as well. Deficit here is defined as a hot water draw with an ending water temperature of 41 ºC or less. Figure 6 shows results for the two test units located in Georgia. The horizontal bars labeled “Resistance Mode” on the two graphs of Figure 6 (and Figure 7) indicate time periods when the test unit operated in EWH mode. The data show that daily values of total water use, number of water draws and number of deficits were about the same in both HPWH and EWH modes. Total deficits for both units were about 4-5/d or about 4% to 8% of the draws.

Cooling and dehumidification performance in the HPWH mode for these same two units (one in an unconditioned location and the other in a conditioned location) is shown in Figure 7. For the Gainesville site, cooling was provided to the space where the HPWH was located but obviously did nothing to offset the conditioned space cooling load of the house. A dehumidification benefit of about 1.9 to 3.8 L/d was provided to the space during the summer but little or none during the winter. For the Danielsville site, the modest cooling output of the HPWH offset the house cooling load by about 0.7 kW. Conversely, it added about 1.1 kW to the house heating load in winter. During the spring months (when residential cooling systems typically do not operate much) it provided about 1.9 to 2.8 L/d of dehumidification benefit. It provided some dehumidification (<0.9 L/d) during humid days in the fall and winter seasons as well.

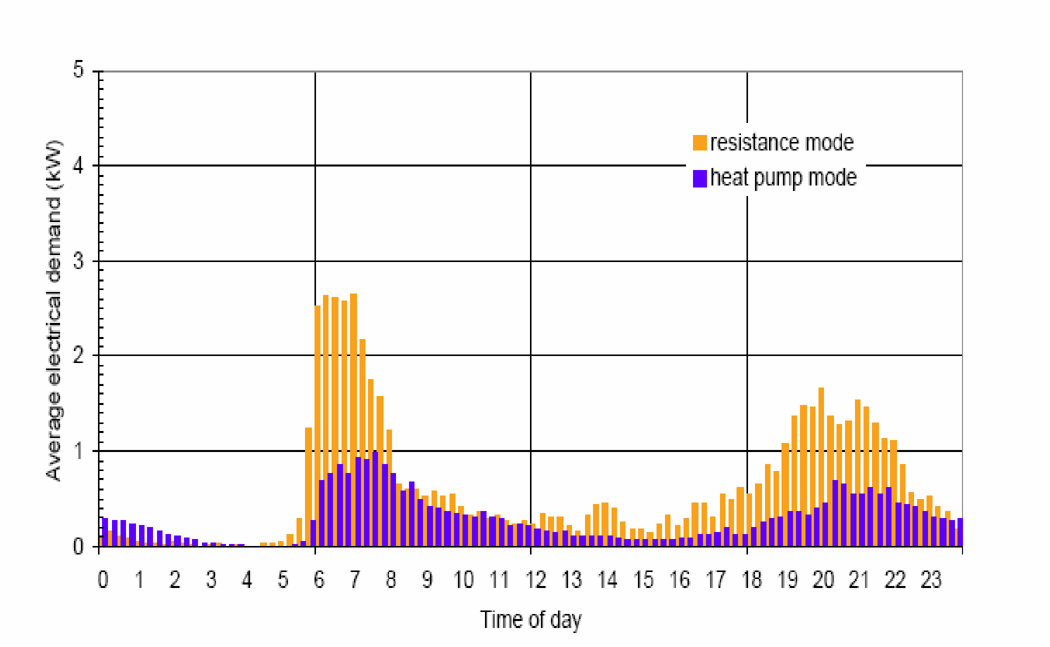


**Figure 4** Wintertime 15-minute weekday diversified peak demand comparison for six test units – HPWH vs EWH.

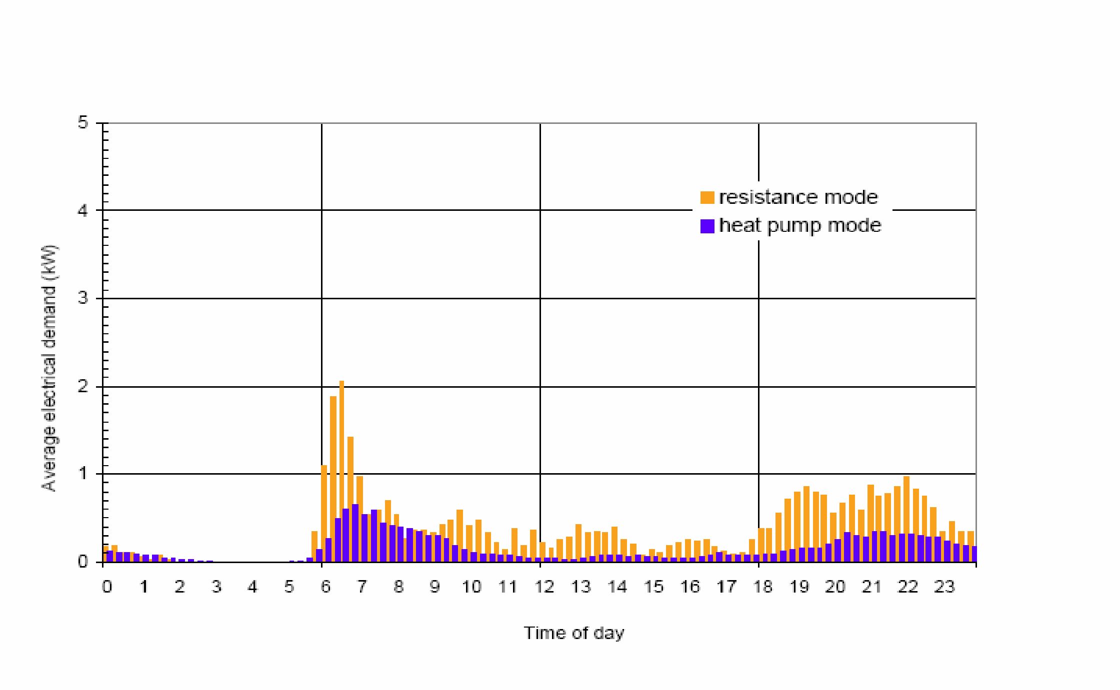


**Figure 5** Summertime 15-minute weekday diversified peak demand comparison for six test units – HPWH vs EWH.

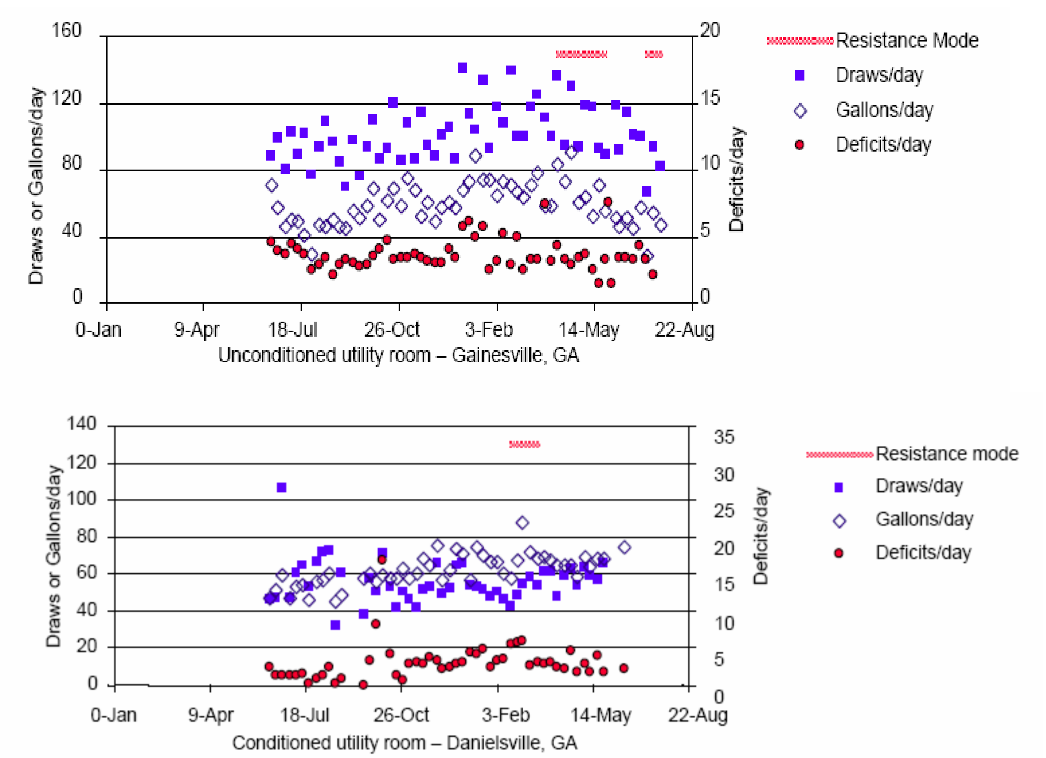


**Figure 6** Daily average hot water draw patterns and deficits for two units.

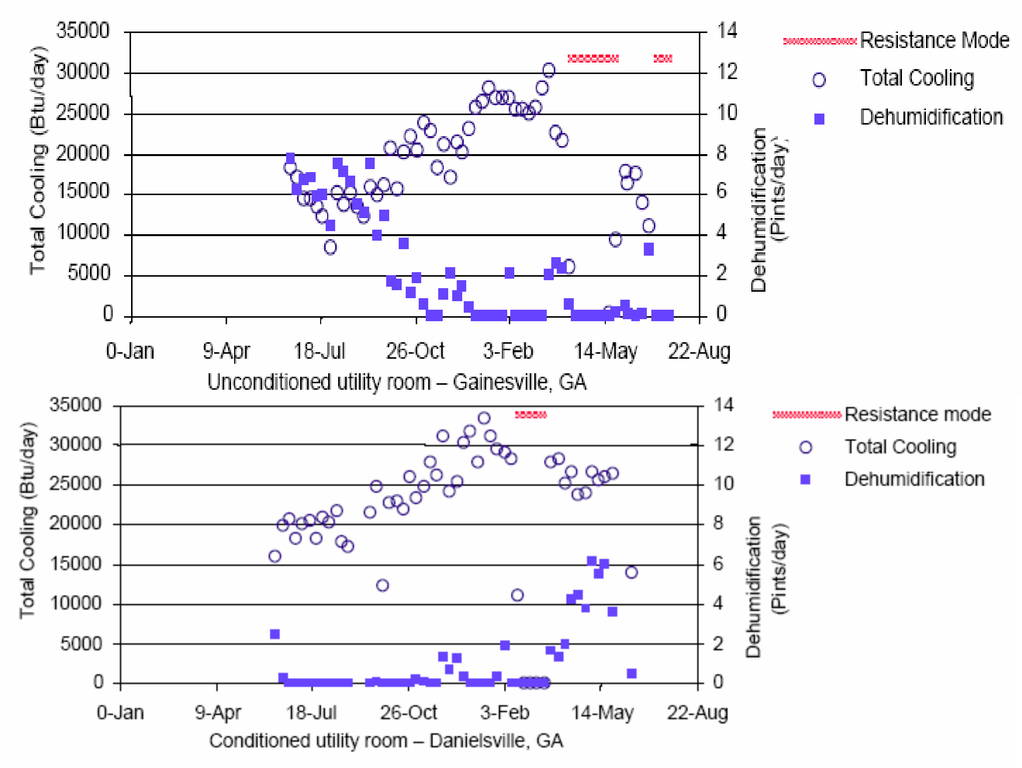


**Figure 7** Daily average cooling and dehumidification performance for two units.

A yearlong field test of 20 of the integral HPWH units was also conducted in California (CEC 2004). Eighteen of the units were installed in residences, one in a commercial office building, and one in a public shower at a marina. Results of the California field test showed that the prototype HPWHs achieved 30% to 50% average energy savings over the EWH baseline in residential applications. In this test baseline EWH performance was simulated using a detailed computer model, and was based on the same water use rates and patterns, hot and cold water supply temperatures, ambient temperature, thermostat setting, and storage tank size as for the HPWH test units. The units performed well even in tight enclosures such as utility closets. Energy Factor (EF) tests were conducted on two of the field-test units using the standard test procedure (Federal Register 1998) before and after the field test. The results showed that the EFs ranged from 2.21 to 2.57, which is reasonably consistent with ORNL's test results for the original prototype. Hot water deficit rates reported in this field test ranged from about 1% to 7% for the residential installations, but participants in general reported no increased "loss of hot water" incidences.

Control system problems similar to those noted in the durability testing plagued many of the units in both the national and California field tests.

### 2.3 Followup Durability Testing

Based on the control system problems experienced during the first durability test program and the two field test programs, a number of recommendations were made for improvement of the integral unit's control system reliability. These include the following.

- Upgrade thermistor sensors to heavier gauge lead wires and eliminate splices.
- Separate low voltage sensor cables from high voltage power wiring to reduce susceptibility to random noise.
- Modify control program to sample thermistor and thermostat inputs multiple times and make control decisions based on the average, helping to offset the impact of a single aberrant reading.
- Institute a vigorous factory quality assurance (QA) program to minimize occurrences such as unsecured thermostats, control boards, and similar items.

The integral unit manufacturer made a number of changes to the control system design both to reduce production costs and to implement the recommendations above. Figure 8 illustrates the major changes made to the control system. Five new HPWH units featuring the new control design were shipped to ORNL for a second round of durability tests. Five of the prototype “add-on” units (Figure 2) were also placed on the durability test stand and were evaluated along with the five integral units.

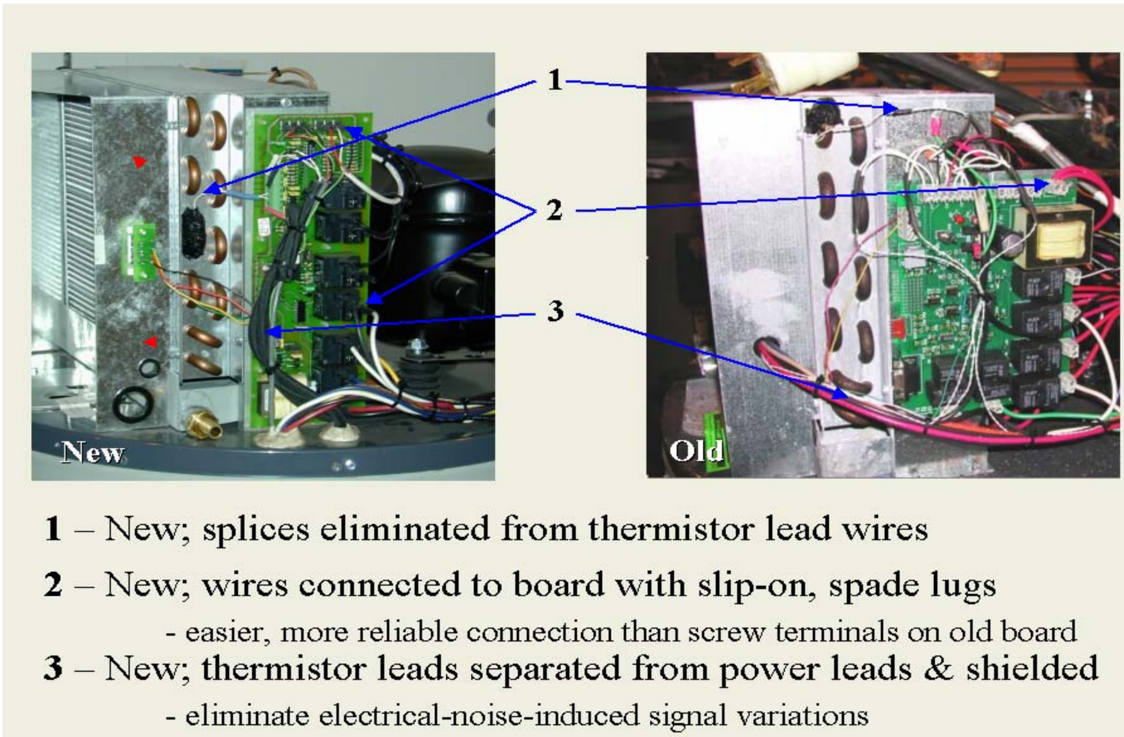


**Figure 8** – New vs. old integral HPWH control board - note changes made in response to durability and field test findings.

The second durability test commenced on February 11, 2003, and continued until November 14, 2003 using the same range of ambient and voltage conditions as for the first round (Table 1). The new integral units experienced no mechanical system or component failures of any kind, nor did they experience any control system failures while chamber ambient conditions were maintained at the planned Stage 1-4 levels. In addition none of the integral HPWHs in Round 2 experienced any erratic behavior of the controls. Results of energy factor (EF) tests conducted on two of the test units before and after the durability run ranged from 2.2 to 2.4 (Baxter and Linkous 2004).

Post-test tank and compressor examination of four of the integral test units revealed no excessive or unusual wear on any components, including the compressor bushings. The updated HPWH controls did not permit compressor discharge temperatures to exceed about 107 ºC during this test period, which would tend to reduce the loading on the bushing.

The add-on units similarly experienced no component or control failures and reliably produced hot water throughout the durability run. As noted earlier, these units were initial production prototypes obtained from the manufacturer for this test. In fact, they were shipped to ORNL before the manufacturer had conducted any internal testing (Johnson 2004). Assembly quality was inconsistent among the five units - a number of problems had to be corrected prior to durability testing. All the problems found can most likely be traced to inconsistent attention to detail during assembly. A rigorous factory quality assurance program would prevent most if not all such problems. In addition, one of the units experienced a 50% loss of refrigerant due to a small leak that developed in its capillary tube near the end of the durability run. A small degradation in unit steady-state COP (about 2-6%) was seen on four of the units. Disassembly and examination of the condensers after the test revealed scale buildup on the waterside surface of the condensers. The scale build up was most likely due to calcium carbonate ($CaCO_3$) precipitation from the water in the test loop. This will likely be a problem for "add-on" type HPWHs depending upon the hardness of the local water. It can be limited somewhat (but not eliminated) by limiting the maximum hot water set point temperature to ≤ 52 °C. This will limit the water temperature in the condenser and reduce deposition rates. During this durability test water temperatures in the condensers of the add-on units exceeded 63 °C regularly.

Energy factor (EF) tests conducted on two of the add-on units before and after the durability run resulted in EFs of about 1.4. The slight reduction in steady-state COP noted above did not noticeably impact the EF results. An increase in EF of 15-20% could be obtained by taking some relatively simple measures – insulate the condenser and hot refrigerant and water lines in the HPWH package and use a more efficient fan motor. Uncertainty for the measured EFs and for the field-test COPs is estimated at ±5% (Murphy and Baxter 2004).

## 3 MARKET STATUS

HPWHs have been on the residential market in the US for over 20 years. There are currently three US manufacturers of HPWHs, one selling an integrated "drop-in" type model and the other two add-on type HPWHs. The total market share of HPWHs is miniscule. Annual shipments of HPWHs peaked at 8,000 in 1985 and had dropped to 2,000/y by 1994 (DOE/EERE 2004). A few thousand units have been installed within the past five years as part of utility incentive programs primarily in the northeastern part of the US and federal and state field test programs. The current manufacturers have sold only a few hundred units to homeowners outside these promotional programs nationwide. Each company currently markets the products via their own distribution channels using existing sales representatives whose main business is other products. Units are made to order and shipped on demand (Ashdown et al 2004).

By contrast, the total US residential water heater market totaled more than 9.5 million units in 2003 about evenly split between gas and electric models. The projected EWH replacement market for 2005 is about 3.4 million units (Appliance Magazine 2004). To achieve a significant market, the HPWH must penetrate this EWH replacement market.

The primary barrier to wider market penetration for the HPWH has been price. Typical installed costs for early models was ≥ $1400 versus $400-$450 for an EWH. Prices for current add-on models range from $900 to $1100 (uninstalled) while the integral unit costs approximately $1200 (uninstalled). Until there is a larger market, these prices cannot be significantly lowered. However, despite these significantly higher costs HPWHs can still achieve paybacks of as low as five years versus EWHs depending upon local electricity prices, water use levels and patterns, and other site-specific conditions (Ashdown et al 2004). Results from the California field study indicate that if the integral unit installed cost could be reduced to $875 payback periods would range from 2 to 3 years in that state where electricity costs about 12 ¢/kWh on average (CEC 2004).

Another barrier is the poor reliability reputation of the early models. While the current product offerings appear to have made great strides in eliminating these reliability issues this historical reputation will take time to overcome. The integral unit manufacturer is offering a 7-year warranty on its product in an attempt to overcome this problem. By comparison, average electric water heater lifetime is about 11 years (DOE/EERE 2004).

Surveys of utilities and HPWH owners were conducted (Ashdown et al 2004). Electric utilities are recognized as having a unique capability to promote energy saving technologies like HPWHs among their customer base. A survey was undertaken to gain some understanding of their perspective on decision criteria and marketing experience for such technologies. Respondents from New York state utilities (small and large) and a New York utility consortium accounted for 58% of the survey sample. The remaining respondents were from other utilities. A number of the significant findings are listed below.

- Consumer interest was an important decision factor for HPWH promotion among the smaller utilities but not among the larger.
- Large utilities cited a need to meet regulatory agencies' requirement that promotions meet "appropriateness tests" like resource cost, societal benefits, etc.
- Familiarity and reliability of the technology were considered more important than energy savings.
- Most New York utilities do not promote energy-efficiency. (The New York State Energy Research and Development Agency assumes the role of energy efficiency promotion in that state.)

An informal survey of seven homeowners with HPWHs was also conducted. Three of the seven had purchased their units on the open market while the others were participants in either the DOE or CEC field studies. Survey findings indicated that energy efficiency and operating cost were less important than reliability of hot water production, unit size (ability to fit within space of previous water heater), and serviceability. Most noted no discernible difference in their monthly electric bills. All mentioned that the HPWHs were noisier than the EWHs they replaced (due to the evaporator fans) but did not consider the added noise overly objectionable. The dehumidification obtained when the units were running was cited as the strongest benefit of the HPWHs. Two of the three homeowners who purchased units indicated that available rebates were their primary incentive.

Three separate participant satisfaction surveys were held during the CEC (2004) field test program. The overall satisfaction rating expressed by the participants ranged from 2 to 5, with an average of 3.4-3.7 (1 = "much worse than previous water heater": 5 = "much better than previous water heater").

## 4 SUMMARY

Heat pump water heaters (HPWH) have significant potential to reduce electric energy consumption for water heating. Two intensive field test programs involving 38 integral-type HPWHs noted energy savings ranging from about 30% to >60% and diversified peak reductions of up to 1.9 kW in winter mornings and up to 0.6 kW in summer afternoons versus EWHs. Despite these encouraging results, the current market share of HPWHs in the US is very small (<1000 units/y) in comparison to the total water heater market (>9.5 million/y) and the EWH replacement market (>3.4 million/y).

Part of the poor market performance of the HPWH is due to the poor reliability record or the first units introduced twenty years ago. To help address this barrier, accelerated life durability tests for current versions of both "add-on" and "integral" type HPWHs have been undertaken. Results for the latest production version of the integral unit used in the field studies noted above indicate that it should reliably produce hot water for at least 10 years, nearly equal to the average 11-year life expectation for EWHs. Energy factors for the test units (measured before and after the durability testing) ranged from 2.2 to 2.4. The manufacturer of this unit is offering a 7-year warranty to further address the reliability issue. The add-on unit tested is a new prototype intended for ease of do-it-yourself installation by homeowners. It, too, survived the durability test program with no complete failures but needs some added development work to achieve consistent manufacturing quality. It could also benefit from some efficiency improvement. The measured EFs for the add-on units were about 1.4 but could be improved by about 20% by insulating the condenser and hot refrigerant lines and by implementing a more efficient fan motor.

First cost of the HPWHs remains the biggest barrier to market acceptance. The currently available HPWHs cost $900 to $1200 versus about $200 for an EWH. With the existing very low sales volumes these prices cannot be lowered much if any at all. Therefore some efforts will be needed by utilities, government, or both to increase the market to a point where cost reductions become more achievable.

A study of HPWH market experiences and acceptance by both consumers and utilities gives some suggestions for improving the market picture. These include the following.

- Manufacturers or manufacturers and government agencies together could engage electric utilities located in areas with the greatest energy and peak savings potential to aggressively market HPWHs in those areas.
- Engage new homebuilders in such areas by including the HPWH as part of an "energy-efficiency" package.
- Consider renaming or repackaging the product to improve consumer perception and emphasize additional ancillary benefits (such as dehumidification capability).
- Engage large do-it-yourself retailers (Lowes, Home Depot, etc.) to facilitate introduction of HPWH technology through that sales venue.

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