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ACCELERATED LIFE TESTS OF A RESIDENTIAL HEAT PUMP WATER HEATER

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ABSTRACT

Ten prototype "drop-in" heat pump water heaters (HPWH) were placed in an environmentally controlled test facility and run through a durability test program of approximately 7300 compressor duty cycles. This durability test was designed to represent seven to ten years of normal compressor cycling to meet hot water needs of a residence. The heat pump portion of the HPWHs experienced no compressor, evaporator fan, or power relay failures during the durability test run. The first generation control system proved to be the least reliable component of the units. Each controller included four temperature sensors to monitor key control parameters. Out of 40 total sensors, 16 failed during the durability program. These failures were due to problems with spliced joints in the sensor lead wires. Efficiency measurements on all units showed that the prototype HPWH is at least twice as efficient as conventional electric resistance water heaters.

INTRODUCTION

The HPWH examined in this study was intended to be a "drop-in" replacement for residential electric water heaters (EWH), and is shown in a schematic cut away view in Figure 1. The design is based on a patented concept originally developed in 1999 (U.S. Patent No. 5,906,109, May 1999; U.S. Patent No. 5,946,927, September 1999). Development of this HPWH design is described fully by Baxter and Linkous (2002) in a detailed project report. Ten prototype units were built and delivered to ORNL in late summer of 2000 for the durability test program discussed in this paper. Another eighteen units were built and sent to ORNL for a DOE national field test program (Murphy and Tomlinson 2002).

The HPWH units are about the size of a vertical cylinder 5 ft (1.5 m) high and 2 ft (0.6 m) in diameter. A small air-to-water vapor compression heat pump unit (about 3400 Btu/h (1 kW) heating capacity), which uses R-134a as the refrigerant, is located on top of a conventional EWH water tank (45.9 gallon (173.5 L) capacity). Heat to the evaporator is provided by ambient air. The unit's condenser coil is wrapped around the bottom two-thirds of the water tank to provide heat to the water. By design, the small compressor takes 6-8 hours to heat up a tank of water from a cold start or about 1.5-2 hours to recover a hot tank after a 10.7-gallon (40.4 L) water draw. Conventional EWH electric resistance heating elements (one at top and one at bottom of tank) are included to provide backup to the heat pump unit (or emergency heating in event of heat pump failure).

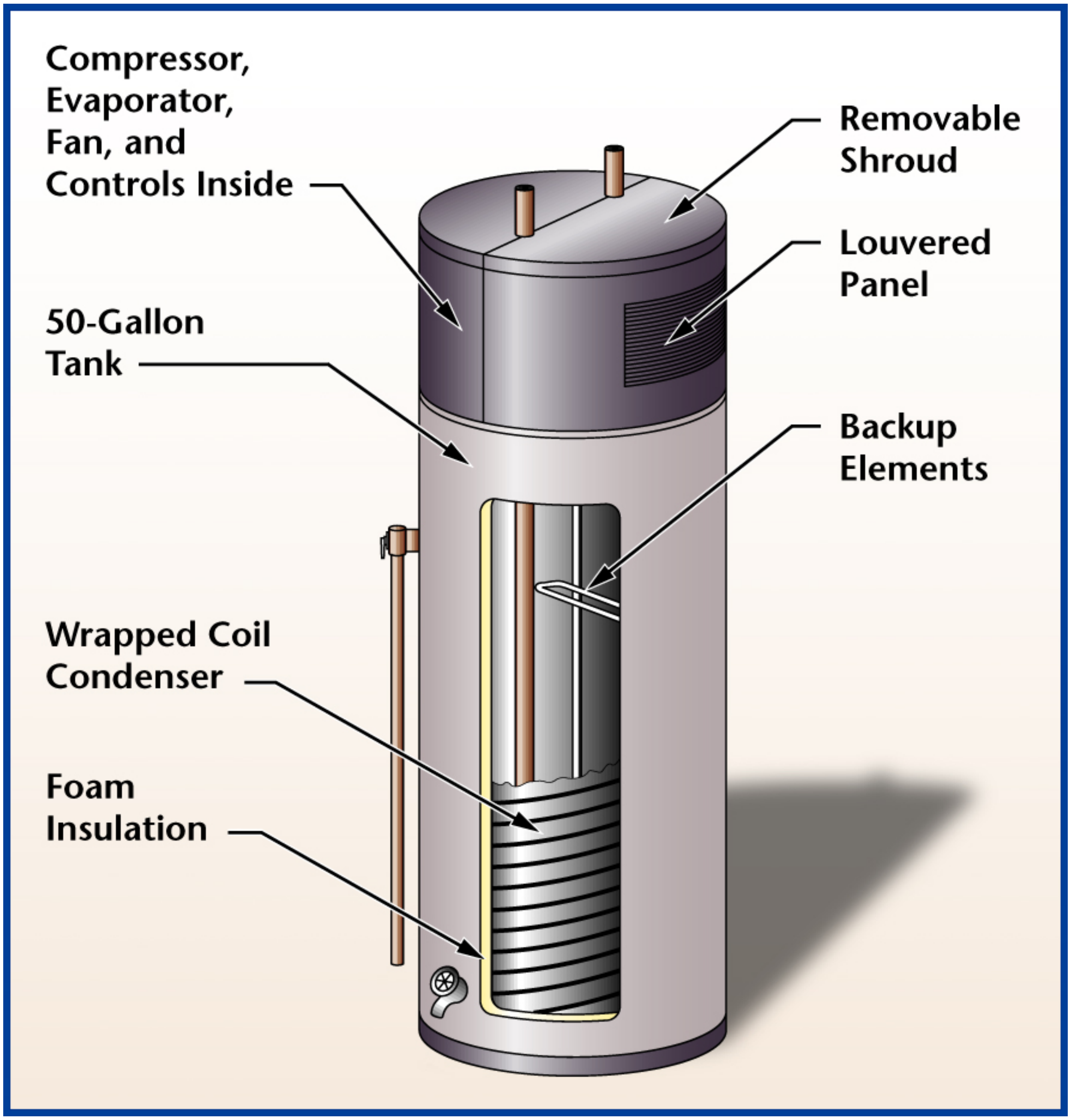

Figure 1: Cutaway schematic view of the HPWH.

The HPWHs were each equipped with a solid-state, microprocessor based control system. The control includes a programmable microprocessor chip, which contains the unit control program, a thermostat (variable resistance potentiometer) and four temperature inputs as listed in Table 1. The control system is powered from the same 240 V, 60 Hz, single-phase source as the HPWH. The controller does not permit the upper element and lower element to energize simultaneously. The software embedded in the microprocessor provides control of the HPWH and determines, based on values of the inputs and the control logic, whether the water heater operates as a

1. Conventional Electric Water Heater (EWH), or a
2. Heat Pump Water Heater (HPWH).

Table 1: Analog & digital inputs to HPWH control system

Input	Device	Units
Dial Thermostat (User Input)	Var. Resistor	Ω
Lower Tank Temperature, T1	Thermistor	Ω
Upper Tank Temperature, T2	Thermistor	Ω
Evaporator Temperature, T3	Thermistor	Ω
Compressor Discharge Temp, T4	Thermistor	Ω

1. TEST PLAN DEVELOPMENT

1.1 Establish Number of Compressor Cycles

Testing of an early prototype of the subject drop-in HPWH according to the DOE 24-h Simulated Use Test (Federal Register, 1998: a reasonable representation of real-world hot water consumption patterns) indicated that the heat pump would cycle on twice during the 24-hour test period. Therefore, assuming the HPWH will undergo an average of two cycles per day in a representative residential application, over a 10-year lifetime the total number of compressor cycles will be (10y)(365 d/y)(2 cycles/d) = 7300 cycles. This estimate of 7300 cycles for a ten-year life was compared to actual field cycling data obtained from the DOE national field test (Murphy and Tomlinson, 2002). An examination of cycling history for three field test units indicates that they experienced anywhere from 14-26 compressor cycles per week, with a slight dependence upon hot water usage, i.e., the greater the usage the greater the number of cycles (see Table 2). For units with high water use, there can be a number of large hot water demand instances each week when the upper element is used for quick recovery of the top portion of the tank. When this happens, the compressor will shut off until upper tank recovery is complete, then it turns back on to finish heating the remainder of the tank leading to a greater number of compressor cycles. Over a ten-year service life, this range of weekly cycling rates would equate to a total of about 7,300 to 13,500 compressor cycles. For sites with low to moderate hot water demand, the 7300 cycle estimate used for the durability testing seems to reasonably represent about 8-10 years of compressor duty cycles. For heavy usage sites, 7300 cycles may represent more like 5-9 years of compressor cycles.

Table 2: Average weekly compressor duty cycles for three field-test HPWHs compared to weekly hot water demand

Approximate weekly water use [gallons (L)]	Weekly compressor cycles	Total compressor cycles for ten years operation at average weekly rate
260 (983)	14-18	7,280-9,360
490 (1852)	15-19	7,800-9,880
630 (2255)	15-26	7,800-13,520

1.2 Durability test protocol

The durability testing consisted of operating the ten HPWH units in an environmental chamber under a set of representative ambient conditions that grew progressively harsher with time and number of cycles. Unit components that failed during these tests were to be repaired or replaced so that, as far as possible, all ten units would complete the entire set of tests. Each unit was instrumented as described in Figure 2 so that changes in the performance of components as well as the unit as a whole with number of cycles could be determined.

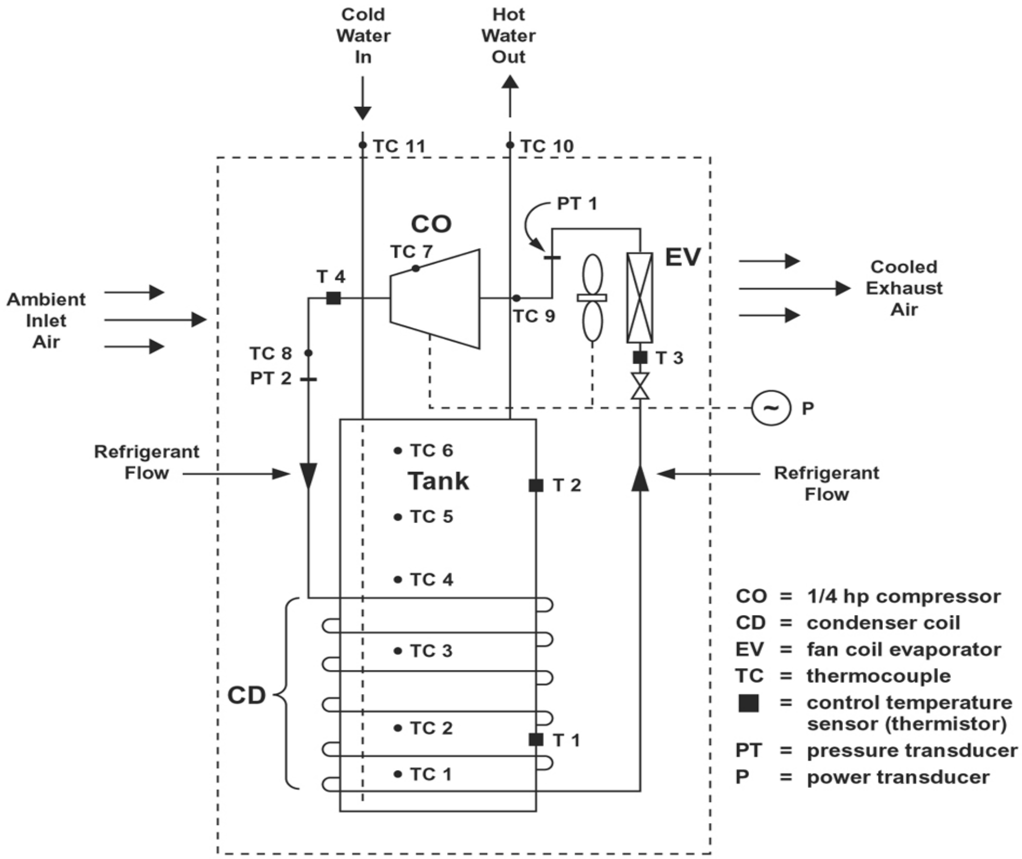

Figure 2: Schematic of HPWH test setup showing data instrumentation locations and control thermistor (T1-T4) locations.

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. This required a laboratory "cycle rate" of less than one cycle each hour. To accomplish this acceleration and to retain real-world tank conditions over each cycle, hot water was introduced into the tank at a rate of 0.2-0.4 gpm (0.0013-0.0025 L/s) to speed tank temperature recovery. This provided the acceleration needed to complete the 7300 cycles in under a year while allowing the condenser and tank operate through the same temperature change as in a real-world application. The test facility used to conduct the durability tests is described by Baxter and Linkous (2002). In addition to accumulating the 7300 duty cycles, the test protocol was designed to cycle the HPWHs under increasingly severe ambient and supply voltage conditions as described in Table 3.

Table 3: Operating conditions for each stage of durability test protocol

Stage	Cycles	Ambient air conditions	HPWH power supply voltage
1	2000	75-80 °F (23.9-26.7 °C) dry bulb temperature 50% relative humidity	240 volts AC
2	2000	75-80 °F (23.9-26.7 °C) dry bulb temperature 80% relative humidity	240 volts AC
3	2000	100 °F (37.8 °C) dry bulb temperature 50% relative humidity	240 volts AC
4	1200	100 °F (37.8 °C) dry bulb temperature 50% relative humidity	192-204 volts AC[a]
5	100	67.5 °F (19.7 °C) dry bulb temperature 50% relative humidity	240 volts AC

[a] five units ran with 192 V supply, one with 196 V, and four with 204 V.

2. TEST RESULTS AND DISCUSSION

The durability test program commenced in mid-December 2000, and continued until October 7, 2001. Table 4 summarizes total cycles accumulated and the approximate operating hours for each unit. Cycle count ranged from a high of 7950 to a low of 6677. Operating hours ranged from about 6000 to about 5200. Unit 6 was off line for about two weeks in late January with a failed evaporator thermistor (T3). Unit 10 was off line for about two weeks in June and July until problems with its lower tank thermistor (T1) were diagnosed. Unit 3 was off line for a total of 33 days in June, July, and August with a variety of thermistor and control board problems.

Table 4: Total cycles and approximate operating hours accumulated by each unit during durability test.

Unit	Total cycles accumulated	Estimated total operating hours
1	7950	5930
2	7696	5940
3	6677	5200
4	7748	5940
5	7213	5970
6	7736	5640
7	7804	5940
8	7349	5930
9	7534	5950
10	7398	5660

The following sections discuss various component problems and failures for the test units, results of post-test examinations of the compressors, condenser wrap, and tanks, and operating characteristics of the units (efficiency, refrigerant operating conditions, etc.).

2.1 System reliability discussion

Table 5 provides a summary of the various component failures experienced by the 10 test units over the course of the durability run. The most immediate point to note is what is not in this table. There were no compressor, fan, or compressor or fan relay failures on any of the units during the durability test sequence. There were instances of refrigerant leakage on two of the units (7&9) during the testing. In both cases these were determined to have occurred at solder joints of discharge pressure transducer fittings. These fittings were added to the test units to facilitate our data acquisition needs. Such fittings would not normally be a part of the system and, therefore, this would not be source of reliability concern for production units.

By far, the greatest source of problems was the control system temperature input sensors (thermistors T1-T4). The thermistors used featured very fine 28 gauge 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. Unit 3 was plagued by the most control system component failures and problems among the test HPWHs. Besides losing five thermistors at various times it also experienced failures of two control boards. Most of these problems occurred during the June-August period (Stage 3 and 4 operation). The combined effect of these various problems caused the unit to be out of service for almost five weeks during that period.

Table 5: HPWH component failure summary

Unit #	Lower tank thermistor, T1	Upper tank thermistor, T2	Evaporator thermistor, T3	Discharge thermistor, T4	Thermostat potentiometer	Control board
1			9/25/01			
2		8/00				
3	7/10/01	7/26/01 9/6/01	11/00	7/10/01 not replaced		7/30/01 8/7/01
4		8/00				
5	9/00 7/26/01	7/26/01 8/17/01			7/25/01	
6	7/23/01		2/1/01			
7						
8						
9	10/00					
10	7/25/01					

2.2 Unit performance

Approximate energy factor (EF) values were measured for each of the test HPWHs at several points during the durability test run. These tests were run according to the DOE Simulated Energy Use Test procedure, (*Federal Register* 1998) however, the ambient temperature and supply voltage conditions varied from the standard values specified in the procedure. The supplemental hot water feedback flow was inactive during these EF tests. Summary results are given in Table 6. Tests were run for each unit in Stages 2-5 of the protocol.

Table 6: Energy factor, EF, test results during various points in durability test sequence.

Unit #	Stage 2 April, 2001	Stage 3 June, 2001	Stage 4 August, 2001	Stage 5 October, 2001
1	2.19	2.49	2.14	1.95
2	2.38	2.25	2.16	1.80
3	2.36	2.52	2.44	1.99
4	1.90	2.01	2.16	2.08
5	2.37	2.28	2.53	2.14
6	2.06	2.41	2.36	2.05
7	2.35	2.36	2.10	2.08
8	2.15	2.31	2.23	1.87
9	2.10	1.67	1.85	1.48
10	2.18	2.47	2.19	1.91

Apart from unit 9, whose EF performance in Stages 3-5 was degraded due to refrigerant loss, the EF results do not vary very much from unit to unit. Unit 5 on average had the highest EF values and unit 4 had the lowest. The percentage difference between high EF and low EF among all of the units in each of the tests (excluding unit 9) ranged from 16% to 20%. Results of calorimeter tests of several of the compressors are given in Table 7 along with the manufacturer's reference values (for new compressors). None of the compressors tested show any capacity or EER loss compared to the "as new" performance levels. In the case of compressor 9, this provides further evidence that the degradation in performance seen by HPWH unit 9 was due to its refrigerant loss and not to any system or component degradation.

Table 7: Compressor calorimeter test results [130 ºF (54.4 °C) saturated condensing temperature; 45 ºF (7.2 °C) saturated evaporating temperature; 220 Volts, 60 Hz power supply]

Compressor	Test date	Capacity (Watts)	Power (Watts)	COP
1	2/15/02	1043.5	443.8	2.35
2	12/4/01	1028.6	445.5	2.31
4	2/15/02	1081.8	444.6	2.43
7	12/4/01	1047.3	461.2	2.27
8	2/15/02	1029.1	451.5	2.28
9	2/15/02	1061.4	450.4	2.36
10	2/15/02	1051.4	450.0	2.34
Reference[a]	-	1034.6	452.6	2.29

[a] Manufacturer's reference performance in "as new" condition.

The ambient conditions for the Stage 5 tests are closest to those prescribed for the standard DOE test procedure. EFs for that series ranged from 1.80 to 2.14. These values compare fairly well with the performance values achieved by units field-tested in residences in several locations throughout the US (Murphy and Tomlinson, 2002).

3. OBSERVATIONS AND RECOMMENDATIONS

Based on the operational experience and test results from the 9-½ month durability run, the following observations and recommendations are noted.

1. The basic heat pump system hardware seems to be very robust. During the entire durability run (and the 3-month pre-test check out period prior to the durability testing) no compressor, fan, or power-switching relay failures were experienced. Two units (7&9) experienced refrigerant leaks. However, the leaks occurred at solder joints in pressure transducer fittings that were added to the compressor discharge lines to enable pressure measurement. These extra fittings will not be included in the normal production units and thus do not represent a reliability concern.

2. The units' efficiency as compared to an EWH baseline looks very promising. Approximate energy factors (EF) measured at different times throughout the durability run were at least 2x that of conventional EWHs.

3. Efficiency of the durability test HPWHs did not appear to have degraded significantly as a result of undergoing over 7000 repetitive duty cycles.

4. The approximately 7300 compressor duty cycles accumulated by the durability test units is representative of about 8-10 years of compressor duty cycling for applications having low-to-moderate hot water demand [<500 gallons/week (1890 L/week)]. For heavier water usage sites, 7300 compressor cycles may be more indicative of perhaps 5-9 years of operation.

5. The first generation control system included on the durability units was the primary source of reliability problems. In particular, sixteen temperature input sensors (thermistors) failed – a 40% failure rate. Two control boards also failed. As a result of this test program, fixes to these problems have been identified that should result in very reliable production units.

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REFERENCES

Baxter, V. D. and R. L. Linkous, 2002, *Durability Testing of a Drop-In Heat Pump Water Heater*, ORNL/TM-2002/92, Oak Ridge National Laboratory, 79 p.

Federal Register/ Vol. 63, No. 90/ Monday, May 11, 1998/ Rules and Regulations/ pp 26012 – 26015.

Murphy, R. W. and J. J. Tomlinson, 2002, *Field Tests of a "Drop-In" Heat Pump Water Heater*, ORNL/TM-2002/207, Oak Ridge National Laboratory, 53 p.

U.S. Patent No. 5,906,109, "Heat Pump Water Heater and Storage Tank Assembly," May 25, 1999.

U.S. Patent No. 5,946,927, "Heat Pump Water Heater and Storage Tank Assembly," September 7, 1999.