Development Of A Low-Cost Heat Pump Water Heater For Residential Applications

Robert A. Zogg, Arthur D. Little, Inc., Cambridge, MA
Edward Barbour, Arthur D. Little, Inc., Washington, DC
Brian J. Nowicki, Arthur D. Little, Inc., Cambridge, MA
John T. Dieckman, Arthur D. Little, Inc., Cambridge, MA

ABSTRACT

Air source heat pump water heaters (HPWHs) have been available in the U.S. since the early 1980s, but never reached annual sales greater than 10,000 units. While HPWHs can offer energy savings of as much as 67% over conventional electric resistance water heaters, their relatively high first cost has kept them from obtaining significant market penetration. In order to bring the energy savings benefits of HPWHs to the general water heating market, it is essential to substantially reduce the installed cost.

This paper describes the development of a new heat pump water heater designed to provide reasonable energy efficiency at a substantially reduced first cost. Water heating simulations, conducted using the WATSIM analysis tool, showed that a significant amount of the typical consumer's hot water demand could be met using a reduced-capacity heat pump, with the balance of demand being met by supplemental electric resistance heating. Reducing the capacity of the heat pump offers several advantages including lower first cost and reduced impact on space heating. The goal of the present development effort was to substantiate a low-cost HPWH design approach in preparation for a broader product and market development initiative.

The design approach was put into practice by modifying a conventional 300 liter (80-gallon) electric water heater. Proof-of-principle laboratory tests were successfully conducted verifying initial performance estimates. The prototype unit was then installed in a five-person household in New England for an extended field test. The unit reliably met the test family's hot water needs throughout the fall, winter & spring and continues to operate.

Introduction

Air-source heat pump water heaters (HPWHs) have been available in the U.S. since the early 1980s, but never reached annual sales greater than 10,000 units (see Figure 1). While HPWHs can offer energy savings of as much as 67% over conventional electric water heaters, their relatively high first cost has kept them from obtaining significant market penetration. In order to bring the energy savings benefits of HPWH's to the general water heating market, it is essential to substantially reduce the installed cost. Additionally, the product also needs to address other market barriers.

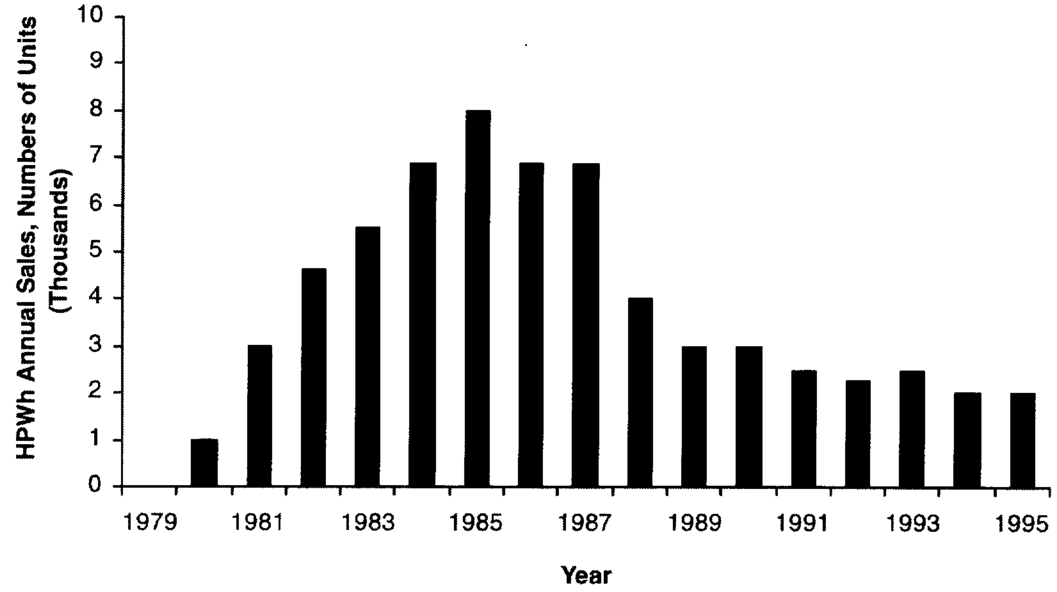

Figure 1: Heat Pump Water Heater U.S. Sales History [1]

Arthur D. Little, in conjunction with the U.S. Department of Energy, responded to the need for a low-cost residential heat pump water heater by identifying and substantiating a novel design approach. The concept makes use of the quick-recovery capability of electric resistance water heating and the high energy efficiency of a heat pump. The heat pump capacity is reduced in such a way as to maintain reasonable energy efficiency yet allow for substantial first-cost reduction.

The following sections describe the design approach and results of the various methods of substantiating this approach including computer simulations, laboratory testing and field testing.

Design Approach

The design approach that was used involves adapting heat pump technology to the residential water heating industry. Since most consumers pay less attention to the actual energy efficiency of a water heater than to first cost, improving cost effectiveness rather than maximizing efficiency is necessary in developing a viable product.

Figure 2 shows the effect of incremental reductions in the energy delivery efficiency of a heat pump water heater on operating cost savings. The savings are calculated relative to a conventional electric resistance water heater with a delivery efficiency of 86%. Delivery efficiency is represented by the energy factor, which for a water heater is calculated from the ratio of delivered energy to input energy and includes both the heat input efficiency as well as tank standby losses. Of particular note from the graph in Figure 2 is that a 23% reduction in energy factor (from 2.6 to 2.0) implies only a 15% reduction in the operating cost savings (from 67% to 57%). Yet by allowing for this reduction in energy factor, significant first cost savings can be achieved which actually improves the overall cost effectiveness of the unit.

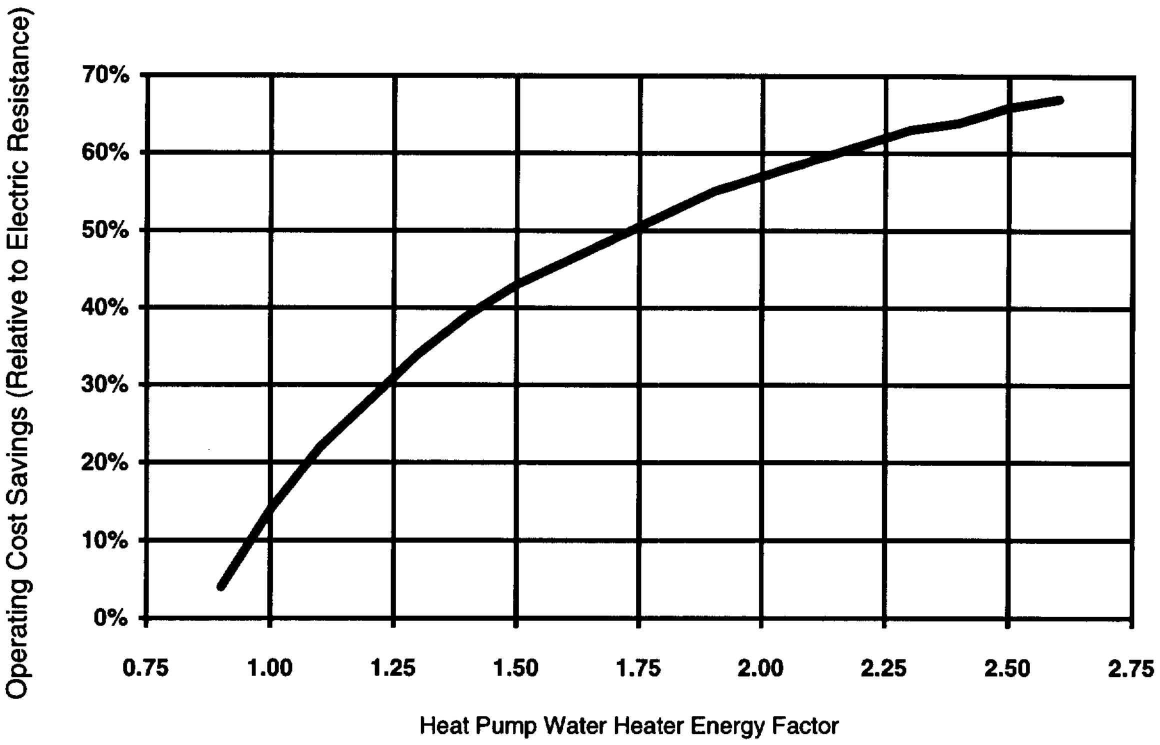

Figure 2: Sensitivity of Operating Cost Savings to HPWH Energy Factor

Greyvenstein and Rousseau [2] demonstrated that the cost-effectiveness of commercial heat pump water heaters could be improved by maximizing the daily run time of the heat pump through size reduction. A similar reduced-capacity approach was employed to develop the present residential HPWH design.

Reducing the capacity of the heat pump offers several benefits including:

1. Reduced system cost (with optimization of system components),
2. Lower negative impact on space heating systems (less by product cooling),
3. Increased heat pump run time through simultaneous electric resistance/heat pump operation which maintains reasonable overall delivery efficiency, and
4. Opportunity for simplified control system.

Verification of the proposed design approach took several forms including computer simulations, laboratory testing and, finally, field testing. The following three sections give the results of these endeavors.

Computer Simulations

A detailed water heating simulation program called WATSIM was used for the computer analysis. WATSIM was developed by the Electric Power Research Institute (EPRI) to simulate the performance of various types of water heaters including electric resistance, heat pumps and desuperheaters. It accounts for such parameters as tank size, insulation, water circulation and mixing induced by water inlet and outlet flows, electric resistance heat inputs and heat pump performance.

Figure 3 below is an example of an initial simulation performed using WATSIM to observe the effect of reducing heat pump capacity. The data shown is based on a 300 liter (80-gallon) heat pump water heater with supplemental electric resistance. The draw conditions are typical of a high-water-using household in New York City (year-round average daily hot water use of 300 liter (80-gallon/day) at 21°C (77°F) temperature rise). The average annual entering water temperatures for each of the cities analyzed come from the EPRI Commercial Water Heating Handbook [3]. The graph shows that a heat pump with a capacity as low as 777 Watts (2650 Btu/hr) could supply roughly half of the annual water heating energy, with the balance being provided by electric resistance heating. It is also apparent that greater increases in heat pump capacity do not significantly increase the fraction of energy supplied by the heat pump.

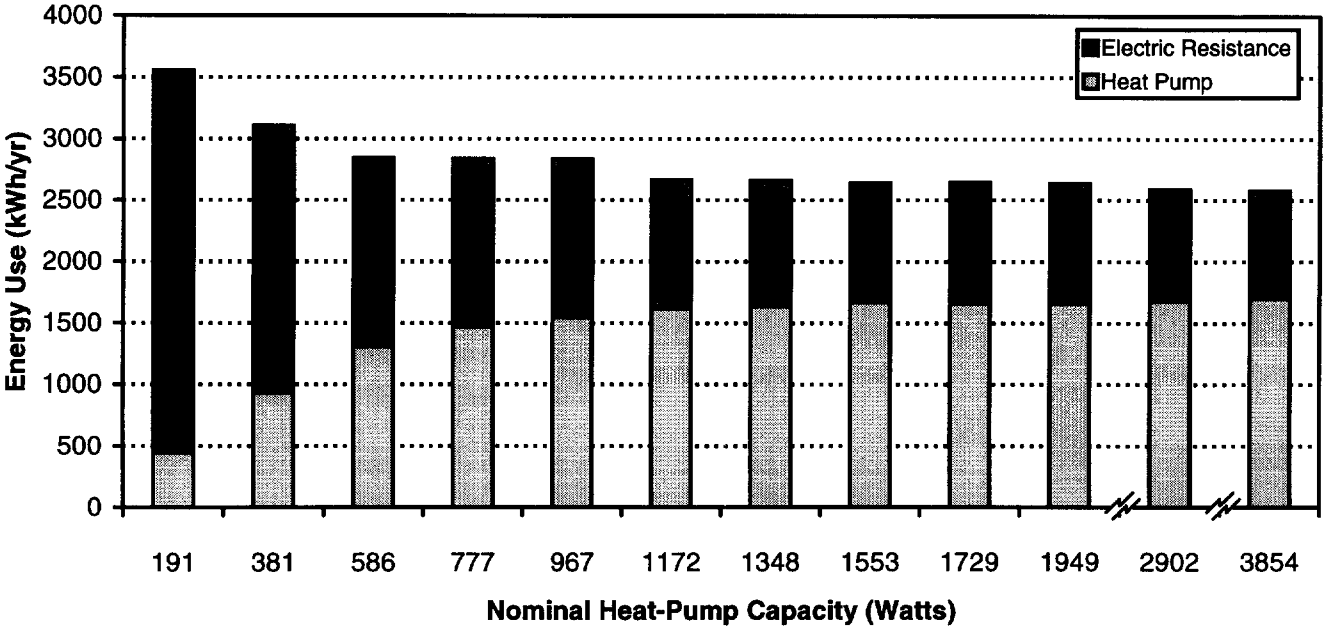

Figure 3: Effect of Reducing Heat Pump Capacity on Energy Use

WATSIM was then used to simulate the performance of an electric resistance water heater (as a basis for comparison) and a heat pump water heater with a reduced-capacity of 970 Watts (3300 Btu/hr). Overall performance is judged by two parameters: delivery efficiency and energy defect. Delivery efficiency is the same as "energy factor" except that it applies to any type of water draw profile, as opposed to the prescribed profile used in U.S. Department of Energy's (DOE) Simulated-Use Test (see Figure 4). It is calculated by dividing the delivered energy by the required input energy. Energy defect gives the magnitude of hot water "short falls" as a way to approximate user satisfaction. It is expressed in units of energy (BTU) and represents the energy required to bring a deficient volume of hot water up to a useable temperature, which is taken to be 41°C (105°F).

The electric resistance and heat pump water heater models were run for three different draw profiles. The first draw pattern used is shown in Figure 4 below and corresponds to the draw profile for the DOE test, which is used to determine the energy factor rating of water heaters in the U.S. The second and third draw patterns are based on actual "real world" profiles for an average size family (2.6 people) and a large family respectively, developed under a separate study [4]. Each of the "real world" draw profiles were run for a cooler-than-average climate (New York City) and a cold climate

(Minneapolis) in the fall and winter. Note that the daily average hot water consumption was adjusted for the various cities and seasons to account for inlet water supply temperature differences.

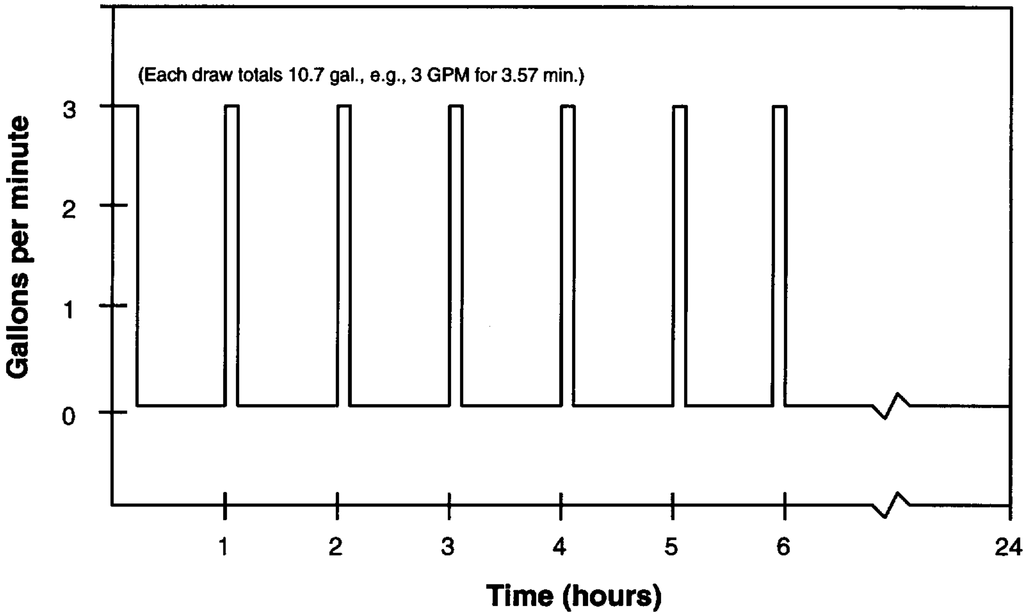

Figure 4: Water Draw Profile for the U.S. DOE Simulated-Use Test

The results are shown in Table 1. The energy factor (at DOE test conditions) of the heat pump water heater was predicted to be 2.04, as compared to 0.84 for the conventional electric resistance water heater. The overall delivery efficiency predicted for actual use ranged from 1.74 to 2.46. The heat pump water heater delivery efficiency ranged from 1.9 to 3.2 times that for conventional electric resistance under similar draw conditions. While the heat pump water heater exhibited higher energy defect values than the electric water heater, these differences were not significant. Both water heaters could be expected to successfully meet the hot water demand in all cases except for a high water use day in the winter in Minneapolis. In practice, in many cases the user is not aware that an energy defect has occurred since it often happens during heavy water use by appliances such as dish or clothes washers. Based on these simulation results, we can conclude that our proposed reduced capacity heat pump water heater design could indeed achieve substantially higher energy efficiency than a conventional electric water heater while offering comparable utility to the consumer.

Table 1: Summary of Performance Simulation Results

Draw Profile	City/Climate	Gallons/Day Averaged Over Week	HPWH		Electric Resistance	
			Energy Defect kWh (Btu)	Delivery Efficiency	Energy Defect kWh (Btu)	Delivery Efficiency
DOE Test	---	64.3	0	2.04	0	.84
Average Size Family Hot Water Use	Min. fall	50	0	2.35	0	.82
	Min. winter.	55	0	2.34	0	.85
	NYC fall	40	0	2.43	0	.76
	NYC winter.	45	0	2.46	0	.80
Large Size Family Hot Water Use	Min. fall	100	0.57(1940)	1.8	0.46(1580)	.91
	Min. winter.	110	2.71(9260)	1.74	2.4(8190)	.92
	NYC fall	80	0	1.98	0	.87
	NYC winter.	90	8	1.91	0	.89

Laboratory Testing

After obtaining promising results from the computer simulations, we put the design approach into practice. This was done by modifying a standard 80-gallon electric resistance water heater. The heat pump was integrally packaged with the water heater tank. The upper electric element was maintained for quick recovery capability. The lower electric element was de-activated.

The prototype unit was subjected to two types of tests: a Performance Map Test and the DOE-Based Simulated Use Test. These two tests along with the final results are shown in Table 2. The results shown in this table were obtained after a series of design enhancements and adjustments. The laboratory testing substantiated the functional capability of the design to successfully heat water over the full temperature regime typical of residential hot water heaters. Further, the energy factor results correlated extremely well with the results of the computer simulations. Namely, the predicted energy factor of 2.0 was experimentally verified.

Table 2: Final Laboratory Test Results of Heat Pump Water Heater Prototype

Test Type	Description	Results
Performance Map	Heated water through entire temperature range with heat pump only; Ambient Temperature = 21°C	Heated water up to 59°C (138°F) Average Heating Rate = 1026 Watts (3500 BTUH)
DOE-Based Simulated Use Test	Applied six water draws totaling 243 liters (64.3 gallons). See Figure 4. Both heat pump and upper electric element operable.	Measured Energy Factor = 2.0

Field Test

After positive results from both the computer simulations and the laboratory testing, it became necessary to test the reduced-capacity design approach under "real-world" operating conditions. A field test was undertaken, in which the prototype heat pump water heater was installed in a household in the greater Boston, MA area. The household consisted of two adults, two teenagers and one younger child. The family's existing hot water system, which was deactivated, consisted of an instantaneous coil water heater inside a gas-fired space heating boiler with a 190 liter (50 gallon) storage tank. Figure 5 shows the prototype unit installed adjacent to the existing storage tank and boiler, in the basement.

A PC-based data acquisition system was configured to record various temperatures (including the internal tank temperature and the hot water supply temperature), water consumption, and electrical power input of the heat pump. Two analog kilowatt-hour meters were also used to record the long term electrical consumption of the electric resistance element and the heat pump separately.

The prototype began operation in October, 1996 and continues to operate. After the first few months of operation, the prototype was adjusted in order to optimize performance. The unit has remained unaltered since January, 1997. Table 3 gives a monthly summary of the data that was collected along with average values taken over the period from January to June, 1997.

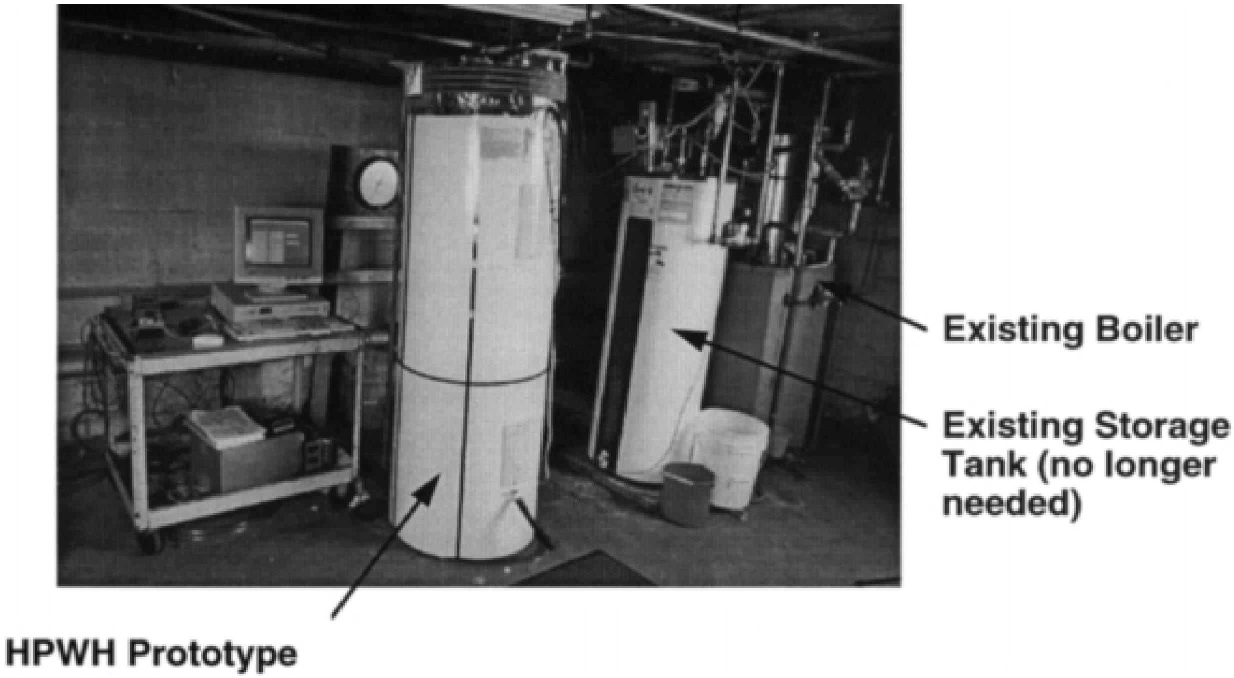

Figure 5: Prototype Heat Pump Water Heater Installed at Field Test Site

The results in Table 3 further substantiated the reduced-capacity design approach. The overall half-year average delivery efficiency of the unit was 2.01. It can be presumed that the full-year energy factor would be equal to or greater than 2.01, since the heat pump could deliver a greater fraction of the water heating energy in the warmer months that have yet to be sampled. The data show an average daily energy defect of 0.15 kWh (507 BTU). This is equivalent to only 3.03 liters @ 43°C rise (0.8 gallons @ 77°F). Most of these defects were probably not detected by the family since they probably occurred during machine water use. Also, the family did not express dissatisfaction with the unit, so it can be presumed that the unit met their hot water utility expectations. The larger defects that occurred during the winter months point out, however, that the heat pump capacity was somewhat undersized for the unusually high level of hot water consumption (570 liters/day, 150 gal/day) of the field test household. The sizing of the tank and heat pump relative to the expected hot water use thus become more critical for this reduced-capacity approach.

Table 3: Summary of Field Test Data

Month	Hot Water Use Gal. per day	Hot Water Supply Temp. °C (°F)	Cold Water Supply Temp. °C (°F)	Energy Fraction Supplied By Heat Pump	Duty cycle of Electric Element	Duty cycle of Heat Pump	Delivery Efficiency	Avg. Daily Energy Defect kWh
January	143	47 (116)	4 (40)	38%	10%	87%	2.01	0.26
February	159	53 (127)	3 (37)	34%	13%	91%	1.97	0.21
March	168	54 (129)	4 (40)	32%	15%	94%	1.91	0.24
April	153	54 (130)	7 (44)	39%	11%	94%	2.01	0.11
May	149	55 (131)	11 (52)	47%	8%	90%	2.13	0.02
June	160	56 (132)	14 (58)	46%	9%	88%	2.06	0.03
Averages	*155*	*53 (128)*	*7 (45)*	*39%*	*11%*	*91%*	*2.01*	*0.15*

Consumer Economics

Though the actual first cost of the heat pump water heater can only be known with greater certainty once the product development cycle is more complete, we have made some preliminary cost estimates. Our analysis indicates that a heat pump water heater designed according to the approach outlined above would have an installed cost premium of roughly $375 over a conventional electric resistance water heater, for all common residential tank sizes. Based on this cost differential, a preliminary consumer economics analysis was performed for low, medium and high hot water use applications in various cities in New England. The results of this analysis are presented in Figure 6. The payback is calculated for the case in which the consumer is faced with purchasing either a new standard-efficiency electric resistance water heater or a heat pump water heater, based on the proposed design approach. The values given reflect the actual marginal utility rates and entering water temperatures [3] of the cities shown. The graph shows that for moderate and severe hot-water-using households in each of the cities sampled, the payback period is about 1 year. This is due mostly to the fact that these cities have colder-than-average (for the U.S.) entering water temperatures and above-average electric rates. The results indicate that it is cost effective for medium-to-large households to take advantage of the energy savings benefits of a heat pump water heater employing the reduced-capacity design approach.

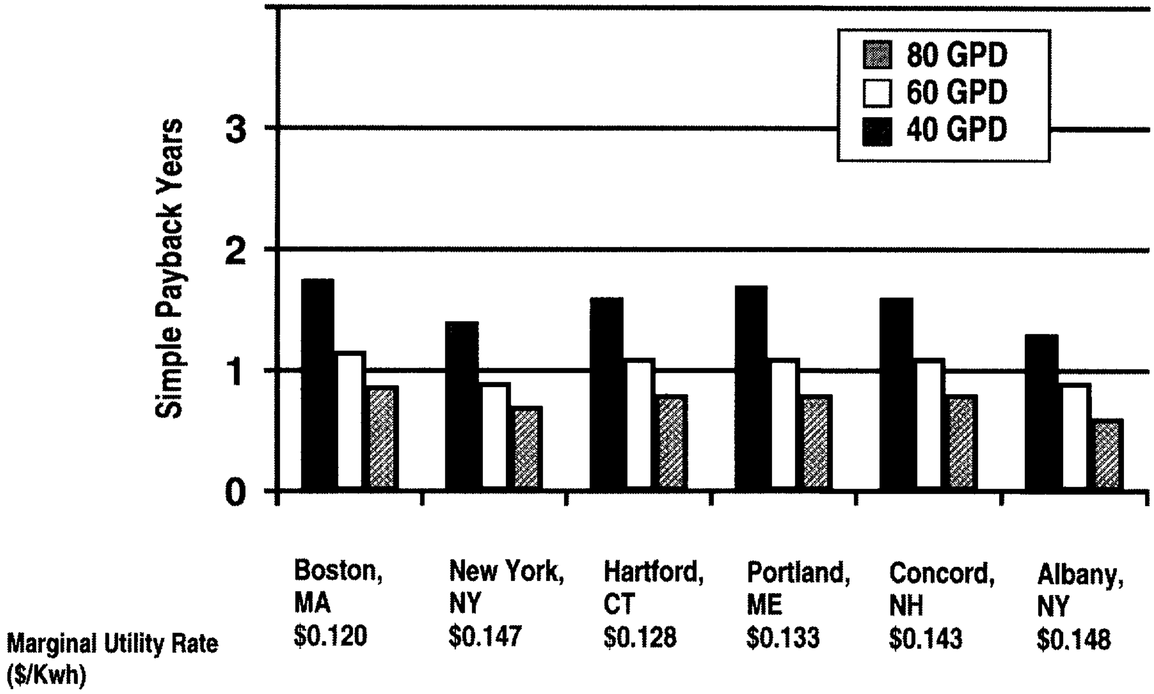

Figure 6: Payback to the Consumer When Choosing the HPWH Over Standard Electric Resistance

Conclusions

The first cost of residential heat pump water heaters must be reduced in order to achieve a greater market presence in the U.S. A design approach aimed at reducing the system cost while maintaining reasonable energy efficiency is proposed. This concept centers around reducing the capacity of the heat pump, which could substantially reduce the cost. The design approach was substantiated through computer simulations, through laboratory testing and by field testing a prototype unit in a household in New England. All three of these methods supported the contention that a reduced-capacity heat pump could indeed provide a significant portion of residential water heating energy, yielding operating cost savings and successfully meeting users' hot-water expectations. Caution, however, must be exercised in sizing the heat pump and hot water storage tank to properly match the hot water use in the desired application. The field test, for example, showed that when the average daily hot water use greatly exceeded the intended design, hot water "short-falls" did occur. Nevertheless, the design approach looks promising, and, therefore, further design, analysis and test is warranted.

Acknowledgement

The authors wish to thank the support of the Department of Energy; Office of Building Technology, State, and Community Programs; Office of Building Equipment. The authors would also like to thank John Ryan, DOE and Jim Brodrick, D&R International, for their guidance during the development of this paper.

References

[1] Barbour, C.E., et al. 1996. *Market Disposition of High Efficiency Water Heating Equipment.* Prepared for U.S. Department of Energy, Washington, D.C., U.S.A. Prepared by Arthur D. Little, Inc.

[2] Greyvenstein, G. P. and Rousseau, P.G. 1996. *Improving the cost effectiveness of heat pumps for hot water installations.* Proceedings of the *5th International Energy Agency Conference on Heat Pumping Technologies*, Volume II, pp. 55-65.

[3] Abrams, D.W. et al. 1992. *Commercial Water Heating Applications Handbook.* EPRI TR-100212, Project 3169-01.

[4] Dieckmann, J.T., et al. 1994. *Technical Analysis of the Proposed DOE Electric Heat Pump Water Heater Energy Efficiency Standard.* Prepared for GAMA. Prepared by Arthur D. Little, Inc.