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Heat Pump Desuperheaters for Supplying Domestic Hot Water—Estimation of Energy Savings and Economic Viability for Residential Applications

M. Olszewski
E. C. Fontana

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Engineering Technology Division

HEAT PUMP DESUPERHEATERS FOR SUPPLYING DOMESTIC HOT WATER – ESTIMATION OF ENERGY SAVINGS AND ECONOMIC VIABILITY FOR RESIDENTIAL APPLICATIONS

M. Olszewski
F. C. Fontana

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ABSTRACT

The heat reclaimer is a double-wall heat exchange system that removes superheat from the heat pump (or central air conditioning) cycle and uses it to heat water for domestic uses. During summer operation, this heat would normally be rejected to the atmosphere without being used. Thus, water heating is accomplished using essentially no primary fuel. In winter, the heat extracted from the cycle would have been used for space heating. However, energy savings are possible above the heat pump balance point because water heating is performed at an enhanced efficiency.

Potential energy savings and economic viability of the heat reclaimer were determined for 28 sites throughout the United States. These results indicate that the heat reclaimer is not economically attractive compared with gas- or oil-fired water heating systems. However, it is competitive with electric resistance water heaters.

Based on these results, a calculational scheme has been developed that could be integrated into the model audit procedure.

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1. INTRODUCTION

1.1 Background

A number of research tasks have been included in the Residential Conservation Service (RCS) Program. Generally, these research tasks are aimed at improving the understanding of energy and cost savings associated with specific conservation measures. It is intended that this will lead to improved audit techniques, which can result in more reliable information being given to consumers concerning energy conservation actions that are cost-effective.

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*Student at The University of Tennessee, Knoxville.

The heat reclaimer for domestic hot water (DHW) heating is a conservation measure added to the RCS audit procedure in Alabama, Arkansas, Arizona, Florida, and Nevada. The purpose of this study was to analyze the heat reclaimer option, quantify energy and cost savings, and develop a procedure by which energy auditors can determine the economic merits of the measure and thereby make recommendations to the homeowner.

As shown in Figs. 1 and 2 (from Ref. 1), the heat reclaimer is a heat recovery device that links the hot water heater and the heat pump (or central air conditioning unit). It is designed to reclaim heat from the hot gas discharged by the heat pump (or central air conditioner) compressor. The recovered energy is then used to heat water for domestic uses.

The energy savings depend in part on the size of the hot water storage tank. The larger the tank, the greater the probability that heat can be transferred to the water supply system when it is available from the

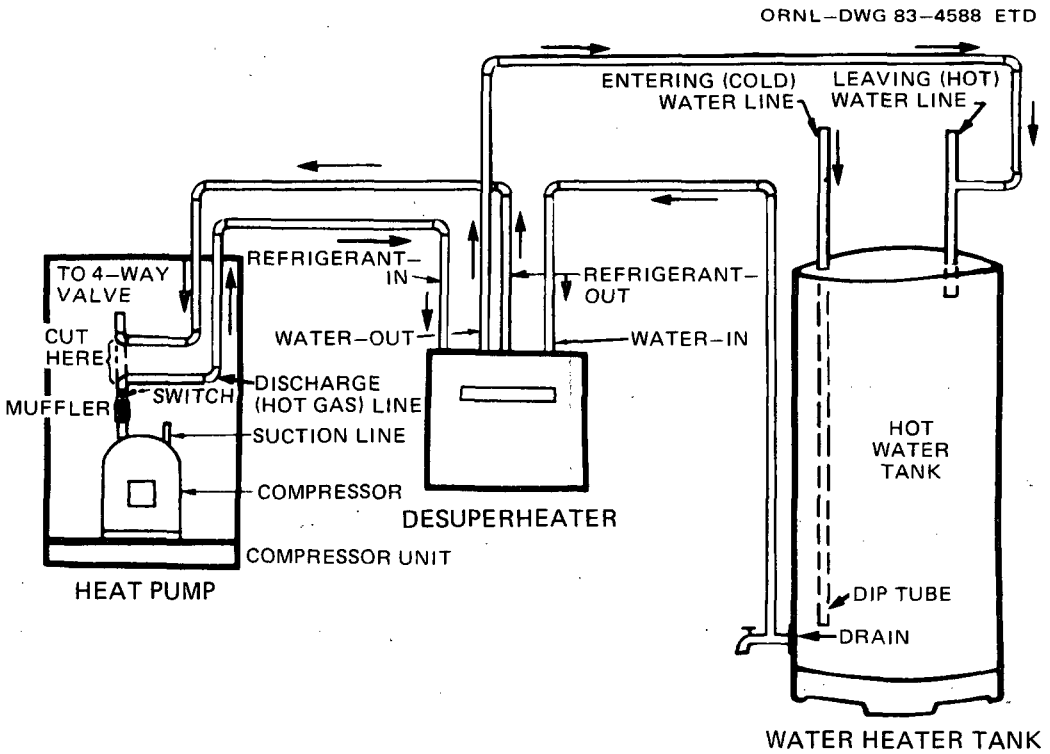

Fig. 1. Recommended installation method for heat reclaimer.

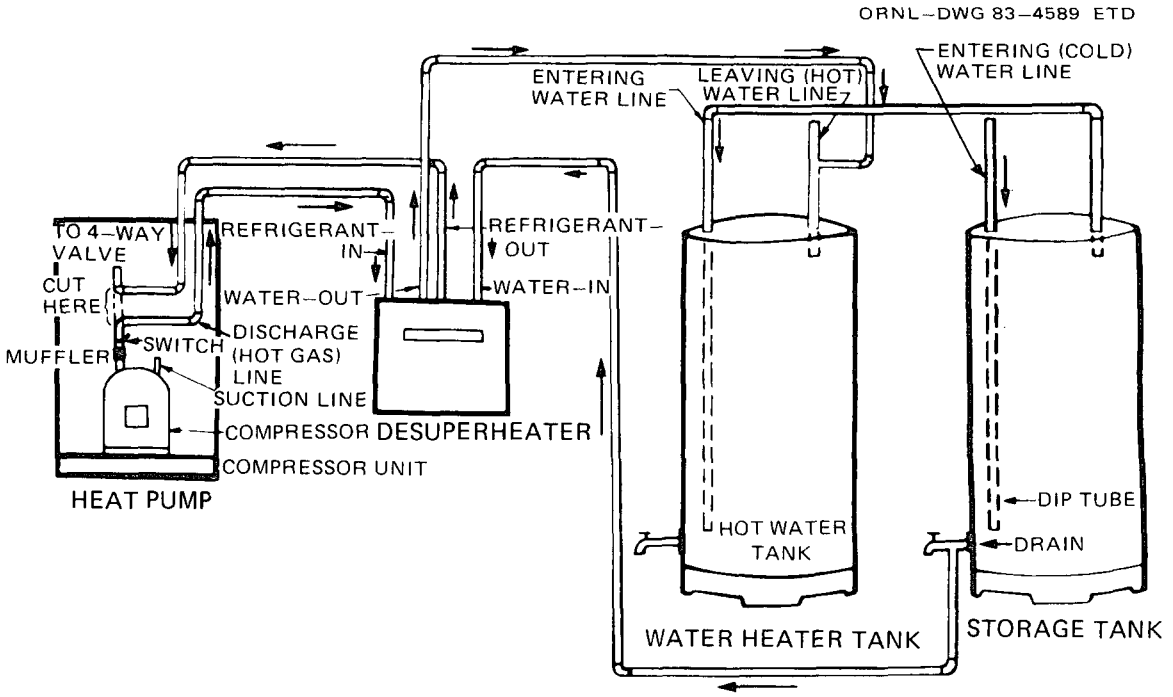

Fig. 2. Alternate installation method for heat reclaimer.

heat pump. Field test results[1] have indicated that, for an average family, capacity problems are evident when only a normal size (~40 gal) water heater is used. Based on these results, it has been recommended[1] that one 80-gal heater with the bottom element disconnected or two 40-gal tanks piped in series (allowing one to serve as a storage tank) be used in conjunction with the heat reclaimer. In the two-tank system, the storage tank heating elements should be disconnected. This configuration (Fig. 2) is a likely candidate for retrofit applications.

The heat reclaimer has two inlet streams. One is the superheated refrigerant from the compressor, and the other is from the drain outlet of the water heater. The heat reclaimer also has two outlets; one returns the refrigerant to the heat pump condenser, and the other returns the heated water to the water heater. A tube-in-tube (double-wall) heat exchanger configuration is generally used to prevent contamination of either fluid stream in case of a leak in either the refrigerant or water loop as required by equipment codes.

During summer operation, the heat removed from the refrigerant would normally be rejected to the atmosphere. Using this heat in the hot water system, therefore, results in significant energy savings because hot water heating is performed at a reduced energy input (greatly reduced in some cases). Heat supplied to the water during winter operation (in the heating season) is not "free" as in the cooling mode, because that heat would normally be used to satisfy space heating demands. However, energy savings are possible because the water heating takes place at an advantageous coefficient of performance (COP).

To achieve maximum energy savings, it is necessary not only to have sufficient water storage capacity but also to modify the control settings of the hot water heater elements. In a one-tank electrically heated unit, this requires that the bottom element be set as low as possible or disconnected entirely. The top element setting should be reduced to about 49°C (120°F). In a two-tank system, the heating elements in the second (storage) tank should not be connected.

This analysis examined the energy savings and economic benefits (using the simple payback period criterion) of the heat reclaimer device. A modified bin analysis technique was used in evaluating the energy savings. The analysis was performed for 28 sites in the United States to gain an understanding of how the economic viability of the concept was affected by climate and energy prices. Finally, a simplified procedure for estimating energy savings was developed.

1.2 System Description

A typical heat pump operating cycle is shown on the pressure-enthalpy diagram presented in Fig. 3 (from Ref. 2). The enthalpy difference $h_D - h_A$* represents the heating capacity per pound of refrigerant, while the cooling capacity is given by $h_C - h_B$. The compressor work input to the cycle is given by $h_D - h_C$. The amount of superheat contained in the cycle is given by $h_D - h_F$. As shown, this amount represents about 31% of the rated cooling capacity or 25% of the heating capacity of the cycle.

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*Subscripts correspond to lettered points on Fig. 3.

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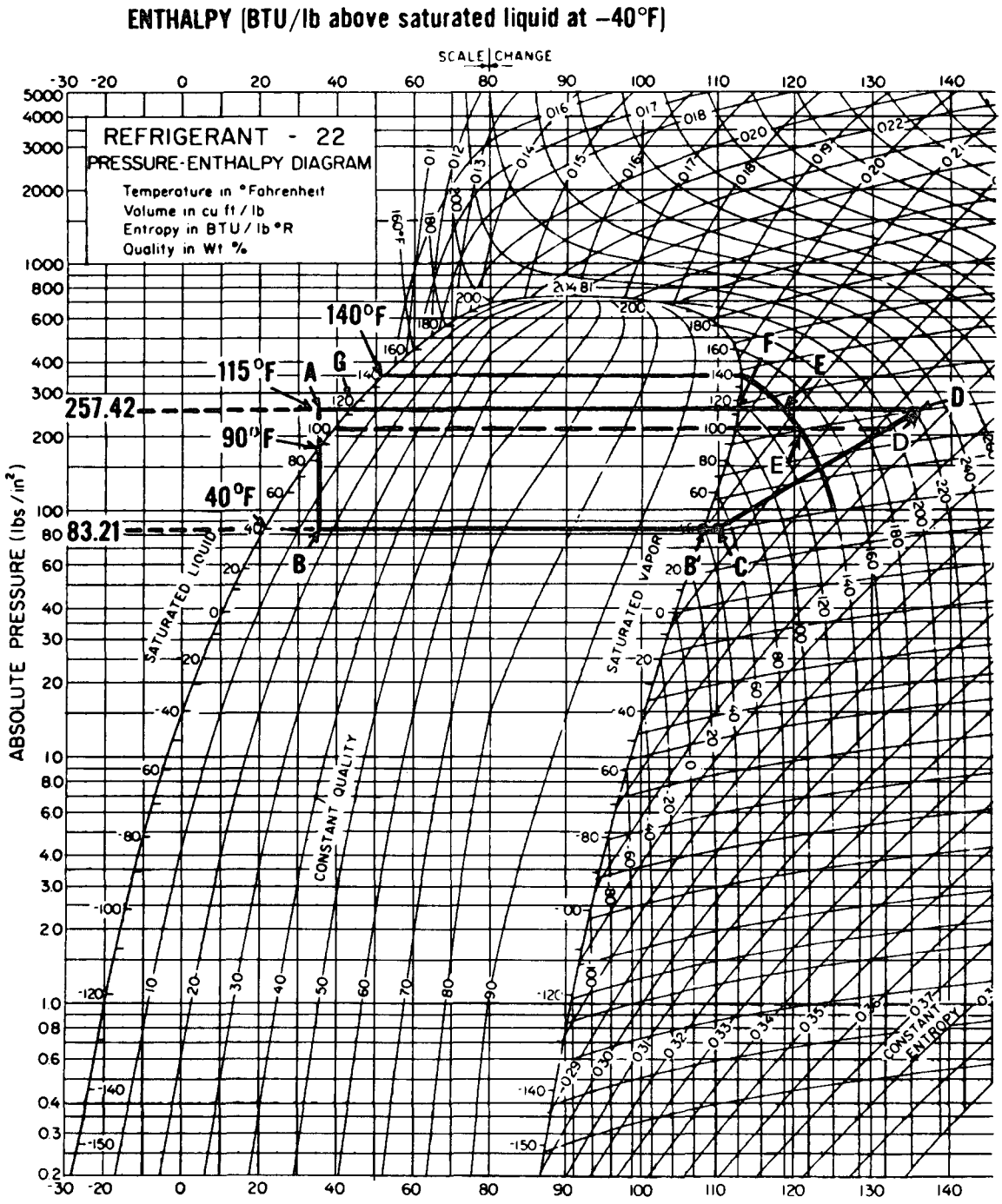

Fig. 3. Typical heat pump operating cycle.

The portion of this quantity of superheat that can be removed by the heat reclaimer depends upon the heat exchanger design and the temperature to which the water must be heated.

For the purpose of this study, three simplifying assumptions were made: (1) the heat reclaimer is capable of heating the water to 60°C (140°F), (2) the heat reclaimer terminal temperature difference (i.e., the difference between the final refrigerant superheat temperature and final water temperature) is 5°C (10°F), and (3) for evaluation purposes the operating conditions of the heat pump (or air conditioning) system (especially the condensing temperature) are as shown in Fig. 3. These assumptions result in the refrigerant superheat temperature being reduced from 104°C (220°F) at point D to 60°C (140°F) at point E. Under these conditions, the quantity of heat removal is 20% of the rated cooling capacity.

During actual service, the heat availability can vary in both directions. A true counterflow heat exchanger with sufficient heat transfer area can generate 60°C (140°F) water with an outlet refrigerant superheat temperature significantly below 66°C (150°F). Therefore, the heat exchanger design can have a significant effect on the amount of heat removed from the refrigerant gas. Another factor influencing the amount of heat available is the actual operating condition of the cycle. On cooler days when the condensing temperature is reduced, the available heat from the refrigerant superheat will be lower. This condition is illustrated by the dashed line on Fig. 3, where the superheat temperature to the heat exchanger is reduced from 115 to 88°C (240 to 190°F). The average operating condition is likely to be somewhere between these two values.

Considering all possible operating situations, 20% of the cooling or heating capacity is considered a reasonable value for an average application. This is consistent with values reported by manufacturers of heat reclaimers[3] and, as will be shown later, is in agreement with field test data.

2. ANALYSIS TECHNIQUE

2.1 General Discussion

Energy savings were calculated using a modified bin analysis technique. Economic viability was determined by calculating a simple payback period. The analysis was performed for 28 sites in the United States to gain an understanding of the relationship between energy savings, economic viability, and climate.

A prototypical house design used for the analysis was an 1800-ft^2 ranch style house with wall and roof R values of 13 and 21, respectively, clear single-pane windows, long sides facing north and south, a total window area of 180 ft^2, and an equivalent internal heat source of 3400 Btu/h. Infiltration was accounted for using the standard Achenback-Coblentz correlation, which relates infiltration rate (in air change per hour) to ambient wind velocity and the temperature difference across the building shell.

Several assumptions were made in the analysis. As previously discussed, it was assumed that 20% of the actual heat pump capacity was available to heat water. Daily hot water use was treated parametrically. As a baseline, it was assumed that 75 gal of hot water was used daily.[4] The economic viability of the heat reclaimer was also examined at 50 and 25 gal/d. The average water delivery temperature was assumed to be 140°F. There is also a 30% allowance for piping and jacket losses. These losses are assumed to be the same for both the conventional and desuperheat water systems. The effect of the pump that circulates water between the heat exchanger and storage tank is assumed negligible. Supplemental water and space heat were assumed to be of the same type and efficiency.

Previous simulation studies of heat reclaimers[2] have indicated that when the water storage volume is equal to an average day's hot water consumption, the bin analysis technique models the system behavior with the same acccuracy of an hour-by-hour simulation that accounts for actual water usage patterns. Because this water storage volume is consistent with recommendation from field test results,[1] it is assumed that the water

storage capacity is sufficiently large to offset the effects of nonsimultaneous operation of the heat pump and use of hot water. Essentially, this results in an assumption (for analysis purposes) that hot water is used more or less continuously at a rate of 75 gal/d (in the base case) or 3.125 gal/h. This flow rate and the inlet water temperature then fix the maximum amount of heat that the water can accept.

The savings associated with a desuperheater water heater, physically linked as it is to the house's heat pump (or air conditioning) system, are a function of the heat pump run time. In turn, the run time is influenced by the house load and heat pump capacity. An existing computer program[5] was used to generate monthly bin loads and design day loads. The design day load was used to size the heat pump system appropriately. The monthly bin load data along with monthly inlet water temperatures[5] were used as input for the heat pump desuperheater computer code developed to perform the analysis. For each location the code calculates: (1) the desuperheater contribution to summer hot water needs, (2) the desuperheater contribution to winter hot water needs, (3) the average COP for water heating, (4) energy savings (in kilowatt hours) as compared with electric resistance water heating, and (5) electricity used by the heat pump to heat water compared with the amount of gas or oil necessary to heat the same amount of water (kilowatt hours traded for gas or oil British thermal units).

2.2 Bin Analysis Technique

The conventional bin analysis technique outlined in the *ASHRAE System Handbook* is a relatively easy and accurate method for calculating annual energy consumption for building heating and cooling equipment without resorting to more involved and costly hour-by-hour simulation techniques. Steady state input energy requirements for the device are computed at different dry-bulb conditions (bins). Each bin typically spans a 2.5°C (5°F) temperature band. Total annual consumption is then computed by weighting each bin by its annual frequency of occurrence.

This standard bin analysis technique is not directly applicable to the heat reclaimer analysis because (1) the heat reclaimer function is not included and (2) it does not include losses associated with cycling, defrosting, and frosting.

However, the standard bin technique can be modified to make it applicable to the case being studied. As previously discussed, it was assumed that the water storage volume was sized properly to offset the effect of nonsimultaneous operation of the heat pump and water usage pattern. With this assumption, the bin analysis technique is an applicable analytic method that yields accurate results. Without this assumption, the more detailed hour-by-hour simulation technique would be necessary. Significant modifications were made in two areas: incorporation of cycling losses and the heat reclaimer.

2.2.1 Inclusion of cyclic losses

The design day load calculations indicated that only 2- or 3-ton heat pumps would be required for the reference house. The steady state heat pump performance characteristics for these units are shown in Figs. 4 and 5. These characteristics represent an aggregate of those heat pumps presently in service.[6]

The total amount of superheat available for heating water depends upon the heat pump run time. Therefore, an accurate account of cycling losses was necessary to properly determine the run time. Three phenomena contribute to a reduction in actual (including cycling effects) heat pump performance as compared with the steady state characteristics[6] shown in Figs. 4 and 5: (1) cycling effects due to operation under partial load condition, (2) frost accumulation during heating operation, and (3) defrosting of the outdoor coil unit. The ratio of cyclic to steady state capacity[6] is given by:

$$\frac{CAP_{cyc}}{CAP_{ss}} = \gamma\ (RT) = \begin{cases} 0.76 \text{ if outdoor temp } < 40^\circ F \\ 0.11(RT) + 0.89 \text{ if heating operation and } T > 40^\circ F\ , \\ 0.26(RT) + 0.74 \text{ if cooling operation} \end{cases}$$

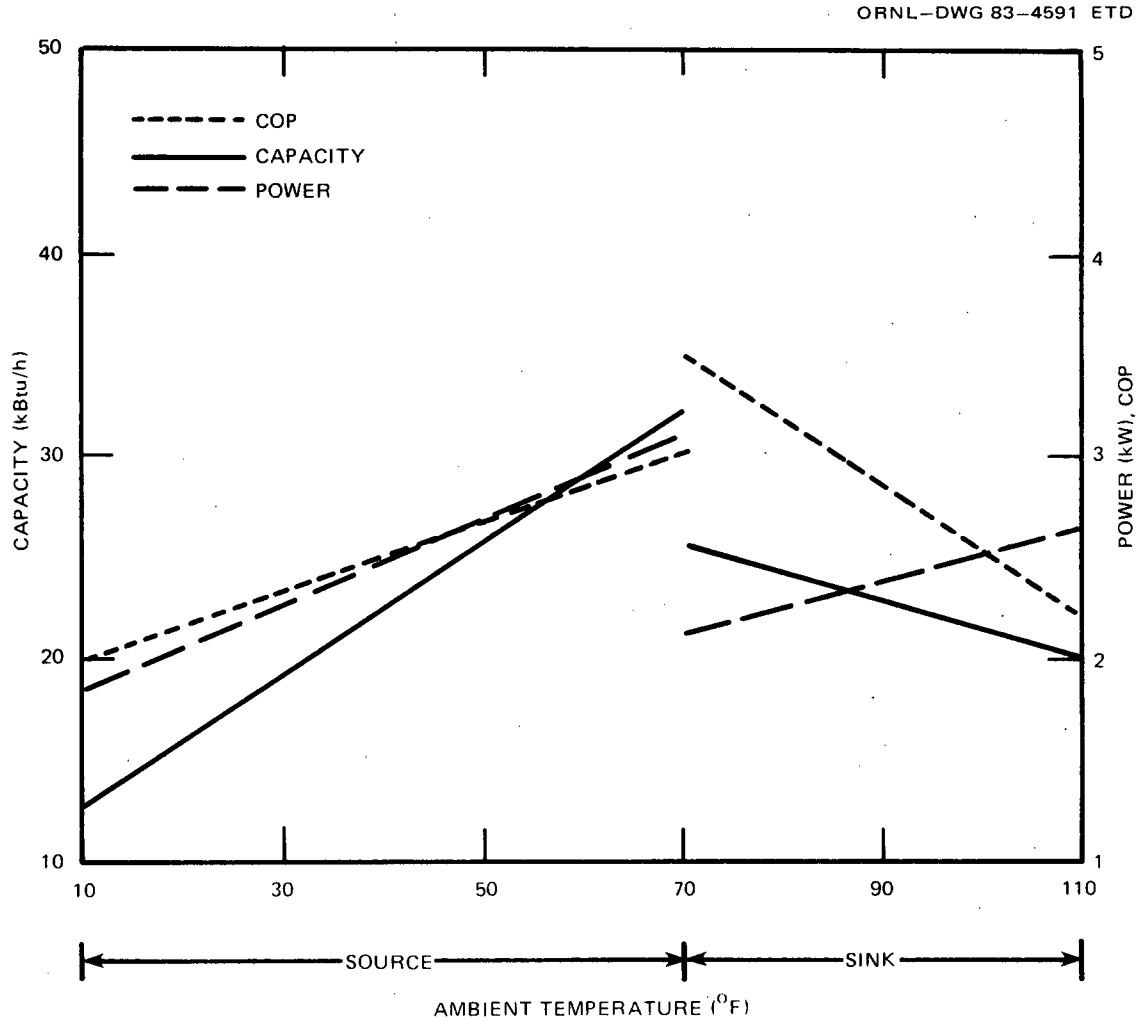

Fig. 4. Performance characteristics for 2-ton heat pump.

where

γ = loss factor,

RT = steady state run time,

CAP_{ss} = steady state capacity,

CAP_{cyc} = cyclic capacity.

The steady state run time (RT) is defined as

$$RT = \frac{\text{space heating or cooling load}}{\text{steady state capacity}} .$$

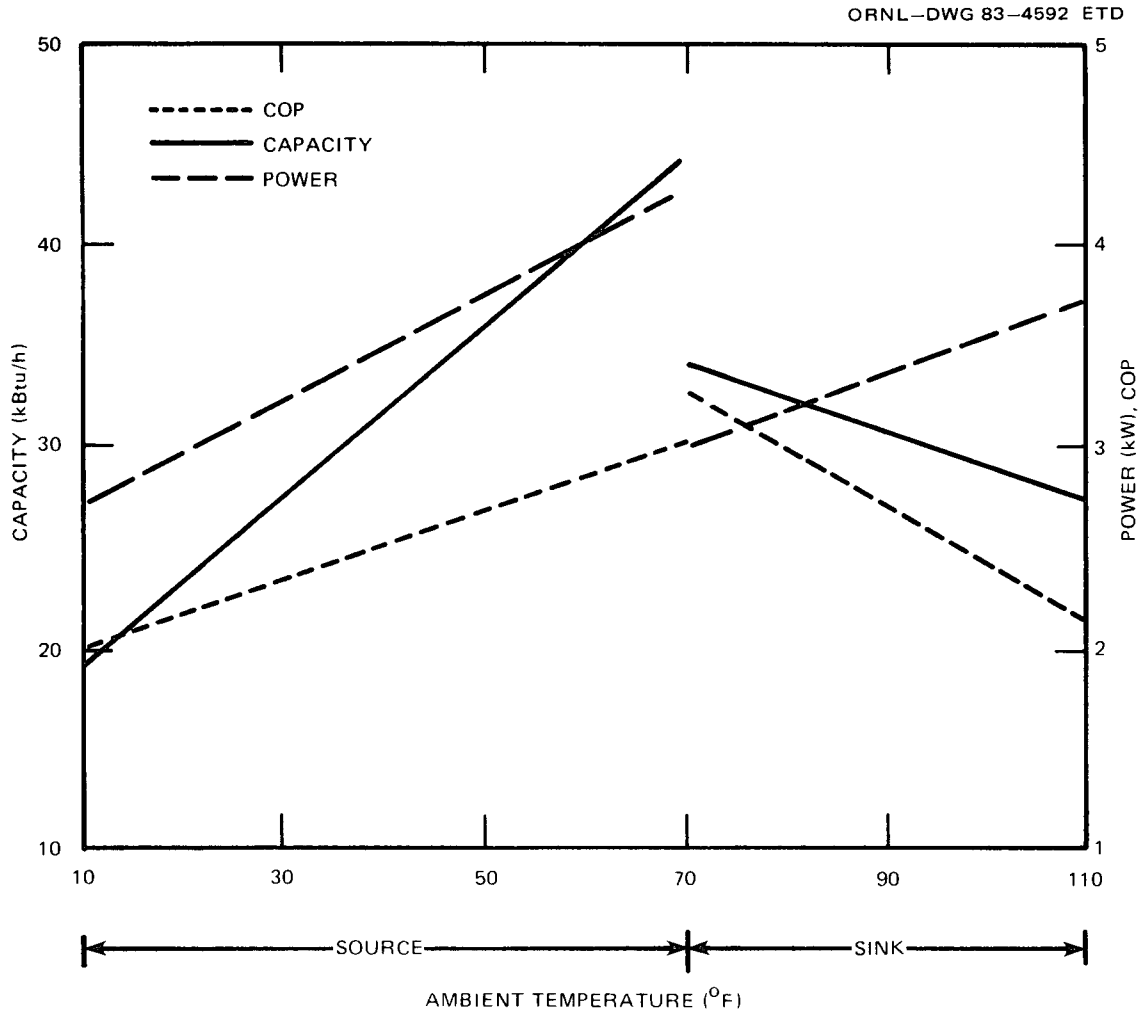

Fig. 5. Performance characteristics for 3-ton heat pump.

2.2.2 Inclusion of heat reclaimer functions

This modification included the effect of the reclaimer on the hot water and space conditioning systems. During summer operation, energy extracted by the reclaimer would otherwise have been rejected to the ambient. Therefore, the heat supplied to the domestic water directly displaces energy that would have otherwise been used to heat the water. Moreover, water heating is accomplished without affecting the heat pump cycle. In winter, the extracted heat would have been used for space heating. Therefore, the space heating capacity is diminished and the heat pump run time is extended. Hot water heating is no longer accomplished

free as in summer. Instead the energy displacement depends upon the COP of the heat pump.

In all cases, the maximum amount of heat capable of being accepted is a function of the assumed water usage. In the base case, it was assumed that an average of 75 gal was used daily. Therefore, the maximum amount of heat that could be accepted by the water (Q_{max}) is given by

$$Q_{max}\ (\text{Btu/h}) = 33.88\ (140 - T_{in})\ ,$$

where T_{in} is the inlet water temperature (°F), which is a function of location and time of year.

During summer operation, the heat available Q_{av} (from the heat pump) for water heating is given by

$$Q_{av}\ (\text{Btu/h}) = 0.20(Q_{cyc})R_s\ ,$$

where Q_{cyc} is the cyclic heat pump capacity previously defined, and R_s is the actual heat pump run time fraction (i.e., run time associated with the cyclic capacity as opposed to RT, which corresponds to the steady state capacity).

In winter, the heat pump run time is extended when heat is extracted from the cycle via reclaimer. The winter heat pump run time (R_w) is given by

$$R_w = Q_L/[0.8(Q_{cyc})]\ ,$$

where Q_L is the house load.

The amount of heat available for hot water heating is then given by

$$Q_{av} = 0.2(Q_{cyc})R_w\ . \qquad (1)$$

Equation 1 is valid only if R_w is unity or less. When heat extracted from the heat pump causes R_w to exceed unity, the available heat is set equal to the amount that can be delivered if R_w is set equal to unity. The available heat is then given by

$$Q_{av} = Q_{cyc} - Q_L\ .$$

If $Q_L \geq Q_{cyc}$, no desuperheat is extracted. The amount of heat actually delivered Q_D to the domestic water is the smaller of Q_{max} and Q_{av}.

The summer energy savings simply equal the amount of heat delivered to the water divided by the efficiency of the heating system. It was assumed that an electric resistance water heater has an efficiency of 100%. Gas- and oil-fired water heaters were assumed to be 70% efficient[7] in the firing cycle.

In winter, the hot water is not free; it is, however, produced at an advantageous COP. When compared with an electric resistance water heater (with a COP of 1), the winter energy savings (WS) are given by

$$WS\ (Btu/h) = Q_D \left(\frac{COP - 1}{COP}\right),$$

when COP is the average seasonal COP of the heat pump. Because energy savings accrue at the end use, the equivalent kilowatt-hour savings are given by dividing WS by 3413 Btu/kWh.

When compared with fossil fuel water systems, a straightforward energy savings calculation is not meaningful because of the difference in unit prices for the respective fuels. In this instance, the increased electricity consumption (AEC) is given by

$$AEC = \frac{Q_D}{COP},$$

while the decrease in fossil fuel (DFF) consumption is given by

$$DFF = \frac{Q_D}{0.70}.$$

The net economic benefit (EB) associated with fuel costs is then

$$EB = (DFF \cdot FP) - (AEC \cdot EP),$$

where FP is the unit cost of the fossil fuel and EP is the electricity price.

Obviously if the relative costs are such that EB is negative, the heat reclaimer is not an economically viable option.

3. TECHNICAL ASSESSMENT RESULTS

Results of the heat reclaimer economic analysis for the baseline case are shown in Table 1. As previously described, the baseline assumptions are an 1800-ft² single-floor house with an average daily hot water consumption of 75 gal. Detailed results of summer, winter, and total annual energy savings are shown for the comparison between heat reclaimers and electic hot water heating. Table 1 also contains the heat reclaimer annual savings in energy cost for each of the competing fuels. This cost saving is simply the total annual energy savings multipled by the prevailing cost for the fuel. In this computation, local electricity costs[8,9]

Table 1. Results of heat reclaimer baseline case economic analysis

Location	Electricity cost (¢/kWh)	Annual energy savings when compared with electric hot water (kWh/year)			Annual energy cost savings ($/year)		
		Summer	Winter	Total	Electricity	Oil	Gas
Albuquerque, N. Mex.	7.6	1373	883	2256	173	62	18
Atlanta, Ga.	6.0	1504	1057	2561	153	80	25
Birmingham, Ala.	6.3	1699	888	2587	164	77	25
Charleston, S.C.	5.6	1813	791	2604	145	79	30
Chicago, Il.	8.0	917	699	1616	129	43	12
Denver, Colo.	7.2	954	756	1710	123	49	13
Falmouth, Mass.	10.8	687	935	1622	176	29	9
Fort Worth, Tex.	6.9	2004	844	2848	196	72	26
Houston, Tex.	6.5	2194	523	2717	176	74	31
Knoxville, Tenn.	4.7	1465	1190	2655	125	96	34
Las Vegas, Nev.	4.5	1808	850	2658	120	87	36
Little Rock, Ark.	4.3	1748	1012	2760	118	96	39
Los Angeles, Calif.	7.5	1097	520	1617	122	45	15
Miami, Fla.	7.8	2602	74	2676	209	65	34
Minneapolis, Minn.	6.4	937	563	1500	96	45	14
New Orleans, La.	6.4	2139	468	2607	167	71	30
Norfolk, Va.	6.6	1488	1149	2637	173	79	20
Oakland, Calif.	8.4	744	844	1588	134	43	10
Phoenix, Ariz.	7.2	1946	580	2526	184	67	25
Pittsburgh, Pa.	8.6	907	776	1683	145	43	12
Portland, Oreg.	3.3	693	1360	2053	68	94	40
Seattle, Wash.	0.9	518	1385	1903	17	110	57
Tampa, Fla.	7.6	2351	193	2550	196	64	31
Trenton, N.J.	8.8	1084	938	2022	176	50	14
Tucson, Ariz.	6.7	1940	654	2594	173	72	27
Washington, D.C.	6.0	1188	1285	2473	148	82	20
Westhampton, N.Y.	10.0	829	984	1813	180	37	11
Winnemucca, Nev.	6.1	1136	789	1925	117	61	19

were used for each site. Because oil and gas prices show much less variation from state to state, average national values were used. The gas price used was $4.89/10^6$ Btu, and the oil price was $9.05/10^6$ Btu (this is equivalent to $1.25/gal).[10] Comparisons of the oil- and gas-fired results are of particular interest because they give an indication of the economic viability of the heat reclaimer option after natural gas prices are decontrolled. It is expected that the price of gas will rise to reach parity with oil (on a cost per unit energy content basis) after price controls are removed.

The electricity savings results (comparing the heat reclaimer to electric resistance hot water heating) show an interesting but expected pattern. Those areas with long summer seasons (the deep South and Southwest) show some of the largest total savings. This is due mainly to the substantial savings accrued during the summer months when the water heating is done solely with reclaimed energy. Locations along the West Coast show winter savings substantially greater than summer savings. The relatively mild winter weather in these areas results in a substantial number of hours where the heating load is below the heat pump capacity, thus allowing the heat pump to operate longer and meet the water heating demand. The results in Table 1 also show that the ability of the heat reclaimer to supply water heating demands is diminished greatly in colder climates. For instance, the heat reclaimer can save 1057 kWh during the winter in Atlanta (a climate that has 2961 heating degree-days[11]) but only about 700 kWh in Chicago (which has 6639 annual heating degree-days[11]).

The energy savings results in Table 1 compare favorably to the limited data available from field tests. A one-year test in the Birmingham, Alabama, area showed an average savings of 2675 kWh (Ref. 1). The eight houses used in the test had an average size of 1850 ft^2 (Ref. 12). The average savings obtained in this test compare favorably with the total savings of 2587 kWh obtained in the computer simulation (Table 1). A test of the heat reclaimer in the Knoxville area showed that 1467 kWh was saved from June through September.[13] Adjusting input parameters of the computer code to reflect the smaller house and slightly reduced hot water consumption values of the test (70 gal/d compared with the 75 gal/d

baseline assumption) yielded a summer savings of 1340 kWh. The simulation results therefore yielded values between 91 and 97% of actual field test results. It appears that the computer simulation results are conservative (i.e., they are on the low side) but are sufficiently representative of actual data that they can be used with confidence in developing a base audit procedure.

The heat reclaimer installed cost varies (sometimes greatly) depending upon the relative location of the heat pump and the hot water heater. Dealer quotes[14,15] yielded an estimated range of $500 to $600. Data obtained from a heat reclaimer retrofit installation at an ORNL experimental house indicated a cost of $560 in 1980 (Ref. 13). It was therefore assumed that the current installed cost for the heat reclaimer unit was $600.

As previously noted, it is necessary to have sufficient storage capacity to decouple the water heating (heat pump run time) and water demand schedules to gain maximum benefit from the heat reclaimer. Field test[1] and simulation[2] data indicate that a total storage volume equal to the daily hot water usage is sufficient to accomplish this goal. In the evaluation it was, therefore, assumed that additional water storage capacity was required when the heat reclaimer was installed. For the base case (i.e., 75-gal/d usage), it was assumed that an additional 30 gal of capacity was installed at a cost of $150 (Ref. 14). The installed cost of the heat reclaimer system was, therefore, estimated to be $750.

The simple payback criterion was used as the standard by which economic viability was judged. The payback period was calculated by dividing the estimated installed cost by the annual energy cost savings in Table 1. The results in Table 2 indicate that the heat reclaimer generally has payback periods in excess of the system lifetime when compared with gas-fired systems. Therefore, it was not considered to be economically competitive when compared to gas-fired hot water heating systems. These results also show that it is not economically competitive with oil-fired systems. The only possible exception is Seattle, where the very low price of electricity (1¢/kWh) is the primary reason for this result. Because of this very limited competitive position, the heat reclaimer option was judged to be uncompetitive with fossil-fueled systems in these cities, and further

Table 2. Simple payback period for heat reclaimer

Location	Payback period (years)		
	Electricity	Oil	Gas
Albuquerque, N. Mex.	4.3	12.1	41.7
Atlanta, Ga.	4.9	9.4	30.0
Birmingham, Ala.	4.6	9.7	30.0
Charleston, S.C.	5.2	9.5	25.0
Chicago, Il.	5.8	17.4	62.5
Denver, Colo.	6.1	15.3	57.7
Falmouth, Mass.	4.3	25.9	83.3
Fort Worth, Tex.	3.8	10.4	28.8
Houston, Tex.	4.3	10.1	24.2
Knoxville, Tenn.	6.0	7.8	22.1
Las Vegas, Nev.	6.3	8.6	20.8
Little Rock, Ark.	6.4	7.8	19.2
Los Angeles, Calif.	6.1	16.7	50.0
Miami, Fla.	3.6	11.5	22.1
Minneapolis, Minn.	7.8	16.7	53.6
New Orleans, La.	4.5	10.6	25.0
Norfolk, Va.	4.3	9.5	37.5
Oakland, Calif.	5.6	17.4	75.0
Phoenix, Ariz.	4.1	11.2	30.0
Pittsburgh, Pa.	5.2	17.4	62.5
Portland, Oreg.	11.0	8.0	18.8
Seattle, Wash.	44.1	6.8	13.2
Tampa, Fla.	3.8	11.7	24.2
Trenton, N.J.	4.3	15.0	53.6
Tucson, Ariz.	4.3	10.4	27.8
Washington, D.C.	5.1	9.1	37.5
Westhampton, N.Y.	4.2	20.3	68.2
Winnemucca, Nev.	6.4	12.3	39.5

analysis concentrated on comparison with electric resistance water heating only.

The results in Table 1 indicate that the heat reclaimer is of interest economically (i.e., a payback period not exceeding 7 years*) in 25

*A payback period of 7 years or less is required for a conservation measure to be included under current RCS rules. Individual states, however, can use other criteria. The 7-year payback criterion contained in the DOE model audit procedures has been used as the economic evaluation criteria in this analysis.

of the 28 cities examined with many showing payback periods of <5 years. Only Minneapolis, with long, severe winters, and Portland and Seattle, with extremely low electricity prices and moderate cooling and heating demands did not show favorable results. The cities showing the greatest potential with payback periods <4 years (Miami, Fort Worth, and Tampa) are located in the southern areas of the country. Each location shows an annual energy savings in excess of 2500 kWh with over 70% of the savings occurring in the cooling season when water heating is supplied with free energy. Each site also had electricity prices 6.9¢/kWh or higher. Ten other sites show reasonably attractive payback periods of <5 years. Some of these sites (e.g., New Orleans and Norfolk) show relatively large energy savings, but the electricity cost is relatively low. Other sites (e.g., Falmouth and Westhampton) show relatively modest energy savings (<2000 kWh annually), but the electricity saved is very valuable. This indicates that climate is not the sole determinant of the allowable cost of the heat reclaimer. Rather, climate determines the energy savings and the energy savings coupled with electricity prices determine the economic benefit.

The analysis was then extended to determine the effect on the payback period of variations in water use and building shell insulation level. Daily hot water use rates of 50 and 25 gal/d were considered, and insulation levels were upgraded to R-38 ceilings, R-21 walls, R-19 floors, and double-pane windows. As shown in Table 3, reduced hot water consumption has a larger effect on the heat reclaimer maximum allowable cost than does higher insulation levels. Reducing hot water consumption to 50 gal/d (a 33% decrease in hot water usage) increases the average payback period by 18%. The 25-gal/d case shows an increase in payback period of 50% (compared to the baseline 75-gal/d case). Increasing insulation to levels that are generally the maximum justified by life-cycle cost analyses increases the payback period by about 10%. These trends are reasonable because the computer simulation indicated that in many instances more heat was available from the heat pump than could be accepted by the water. Decreasing the amount of hot water used decreases the amount of heat accepted by the water. This significantly affects the energy savings and thus the payback period. Increasing the insulation level of the house

Table 3. Effect of water usage and insulation level on heat reclaimer payback period[a] (years)

Location	HUD minimum insulation (gal/d)			High insulation (ft^2)		
	75	50	25	75	50	25
Albuquerque, N. Mex.	4.3	5.3	9.0	4.7	5.7	8.4
Atlanta, Ga.	4.9	5.9	9.5	5.7	6.7	10.2
Birmingham, Ala.	4.6	5.7	9.2	5.3	6.6	9.8
Charleston, S.C.	5.2	6.4	10.5	5.8	7.1	11.2
Chicago, Il.	5.8	6.7	10.4	5.2	5.9	9.1
Denver, Colo.	6.1	7.3	11.9	6.2	7.4	10.7
Falmouth, Mass.	4.3	4.8	7.4	4.2	4.7	7.0
Fort Worth, Tex.	3.8	4.8	8.3	4.3	5.4	8.8
Houston, Tex.	4.3	5.4	9.3	4.6	5.8	9.9
Knoxville, Tenn.	6.0	7.3	11.7	7.3	8.8	12.5
Las Vegas, Nev.	6.3	8.1	13.9	7.3	9.4	14.8
Little Rock, Ark.	6.4	7.8	13.1	7.3	9.1	14.0
Los Angeles, Calif.	6.1	7.0	10.7	7.8	8.8	12.9
Miami, Fla.	3.6	4.8	8.8	3.7	4.9	8.8
Minneapolis, Minn.	7.8	8.9	13.8	7.6	8.6	12.6
New Orleans, La.	4.5	5.6	9.6	4.8	6.0	10.3
Norfolk, Va.	4.3	5.2	8.4	5.1	6.1	9.0
Oakland, Calif.	5.6	6.2	9.4	8.1	8.9	11.9
Phoenix, Ariz.	4.1	5.4	9.3	4.7	6.2	10.2
Pittsburgh, Pa.	5.2	6.0	9.2	5.0	5.8	8.5
Portland, Oreg.	11.0	12.5	20.9	13.7	15.6	21.8
Seattle, Wash.	44.1	49.1	82.0	53.6	60.3	83.3
Tampa, Fla.	3.8	5.0	8.9	4.0	5.2	9.3
Trenton, N.J.	4.3	5.0	8.0	4.3	5.1	7.5
Tucson, Ariz.	4.3	5.5	9.3	4.9	6.2	10.0
Washington, D.C.	5.1	6.2	9.9	6.2	7.5	10.5
Westhampton, N.Y.	4.2	4.8	7.6	4.3	5.0	7.0
Winnemucca, Nev.	6.4	7.8	13.0	6.6	8.0	11.9

[a]With heat pump as source and electric water heater the competitor.

reduces the size and/or run time of the heat pump. Therefore, the amount of heat available is reduced. In most instances this results in the amount of heat available decreasing to a point just below the amount that can be accepted by the water. Therefore, the net energy savings and payback period are affected only slightly.

The effect of house size on the payback period was also examined. If the insulation level remains constant, an increase in house size will result in increased space conditioning loads. In turn, this will require a larger heat pump or run times will be increased for the smaller unit previously specified. In either case, more heat will be available for DHW

heating. The previous results indicated that the amount of heat offered is greater than the amount that can be accepted. Therefore, increasing the amount of heat available from the heat pump would have little or no effect on the energy savings or payback period. Because of this, the sensitivity analysis was performed only for a decrease in house size. As shown in Table 4, decreasing the house size by 17% results in an average increase of only 7% in the payback period. The results of this analysis indicate that summer savings are relatively unaffected because they are limited by the amount of heat that the water can absorb (i.e., fixed by

Table 4. Effect of house size on heat reclaimer payback period[a] (years)

Location	House size (ft^2)		Ratio 1500:1800 (%)
	1800	1500	
Albuquerque	4.3	4.4	102
Atlanta	4.9	5.5	112
Birmingham	4.6	5.1	111
Charleston	5.2	5.7	110
Chicago	5.8	5.8	100
Denver	6.1	6.1	100
Falmouth	4.3	4.3	100
Fort Worth	3.8	4.1	108
Houston	4.3	4.5	105
Knoxville	6.0	6.9	115
Las Vegas	6.3	6.7	106
Little Rock	6.4	6.8	106
Los Angeles	6.1	7.2	118
Miami	3.6	3.7	103
Minneapolis	7.8	7.8	100
New Orleans	4.5	4.8	107
Norfolk	4.3	4.9	114
Oakland	5.6	6.8	121
Phoenix	4.1	4.4	107
Pittsburgh	5.2	5.2	100
Portland	11.0	12.2	111
Seattle	44.1	47.7	108
Tampa	3.8	4.0	105
Trenton	4.3	4.3	100
Tucson	4.3	4.7	109
Washington	5.1	6.0	118
Westhampton	4.2	4.3	102
Winnemucca	6.4	6.4	100

[a]75 gal/d; HUD minimum insulation.

hot water usage) rather than the amount of heat available (i.e., heat pump size and run time). Those areas most affected by house size are the ones where winter savings are an appreciable fraction of the total. Thus, areas with relatively mild winters, where a significant fraction of the heat pump winter run time is at part load, show as much as a 20% increase in payback period.

It is also possible to couple the heat reclaimer to a central air conditioning system. In this case, energy savings accrue only during the summer cooling season. As shown in Table 5, the heat reclaimer is only

Table 5. Heat reclaimer payback period for central air conditioning application[a] (years)

Location	HUD minimum (gal/d)			High insulation (gal/d)
	75	50	25	
Albuquerque	7.2	9.3	16.2	7.4
Atlanta	8.3	10.4	16.8	8.3
Birmingham	7.0	8.8	14.7	6.9
Charleston	7.4	9.4	16.0	7.3
Chicago	10.3	12.0	18.1	10.3
Denver	10.9	13.3	21.5	11.5
Falmouth	10.1	11.8	16.3	10.0
Fort Worth	5.4	7.1	12.6	5.4
Houston	5.3	6.9	12.5	5.2
Knoxville	10.8	13.3	21.3	10.9
Las Vegas	9.2	12.5	22.3	9.4
Little Rock	10.0	12.7	21.8	9.9
Los Angeles	9.1	10.8	18.2	9.5
Miami	3.7	4.9	9.2	3.7
Minneapolis	12.5	14.4	21.7	13.1
New Orleans	5.5	7.0	12.7	5.4
Norfolk	7.7	9.4	15.3	7.6
Oakland	12.0	13.7	24.9	13.2
Phoenix	5.3	7.4	13.6	5.4
Pittsburgh	9.6	11.3	16.7	9.8
Portland	32.8	38.0	64.0	35.2
Seattle	159.1	181.0	291.7	175.0
Tampa	4.2	5.6	10.2	4.2
Trenton	7.8	9.5	14.6	8.0
Tucson	5.8	7.8	13.7	5.8
Washington	10.5	12.8	20.0	10.5
West Hampton	9.1	10.8	15.7	9.1
Winnemucca	10.8	13.8	23.5	11.3

[a]Electric hot water.

viable in the deep South and Southwest, areas that have very long cooling seasons. Even in these climates, it is only viable at the higher hot water usage rates. Evidently, higher insulation levels have a negligible effect on the economic viability of the heat reclaimer.

4. RECOMMENDED AUDIT METHOD FOR EVALUATION OF HEAT RECLAIMERS

The ultimate goal of this study was to develop a calculational method that could be incorporated into the audit procedure. The end result was to be an estimate of the simple payback period, which could be used by the auditor in making recommendations to the home owner. The technical assessment results indicated that, in general, the heat reclaimer device is not economically competitive if gas or oil is used for water heating. Therefore, the audit method concentrates solely on applications where electric resistance water heating is the competitor.

Based on the technical assessment, it is clear that the economic potential is a strong function of annual heating and cooling load of the house and hot water usage. The level of insulation in the home and the size of the residence play relatively minor roles and can be accounted for adequately by the heating and cooling load parameters. The method developed is relatively straightforward and consists of the following steps:

A. Determine annual energy savings
   1. As part of the audit procedure, determine the annual heating and cooling loads for the house.
   2. Determine fractional water heating energy savings.
   3. Adjust savings to account for water usage.
   4. If utility offers split rate, use cooling and heating loads to determine winter and summer (kWh) savings. If central air conditioning is being evaluated, determine summer saving.
   5. Determine annual energy saving (kWh) using fractional saving and normal water heating demand estimated in audit procedure.

B. Determine payback period
   1. Using annual energy savings and local electricity rates, determine annual dollar savings.
   2. Determine payback using annual savings and estimated cost to install heat reclaimer (estimated by auditor).
   3. If payback is <7 years, recommend installation.

The fractional savings (step A.2) are determined using Fig. 6. This figure was derived from the technical assessment results presented in the

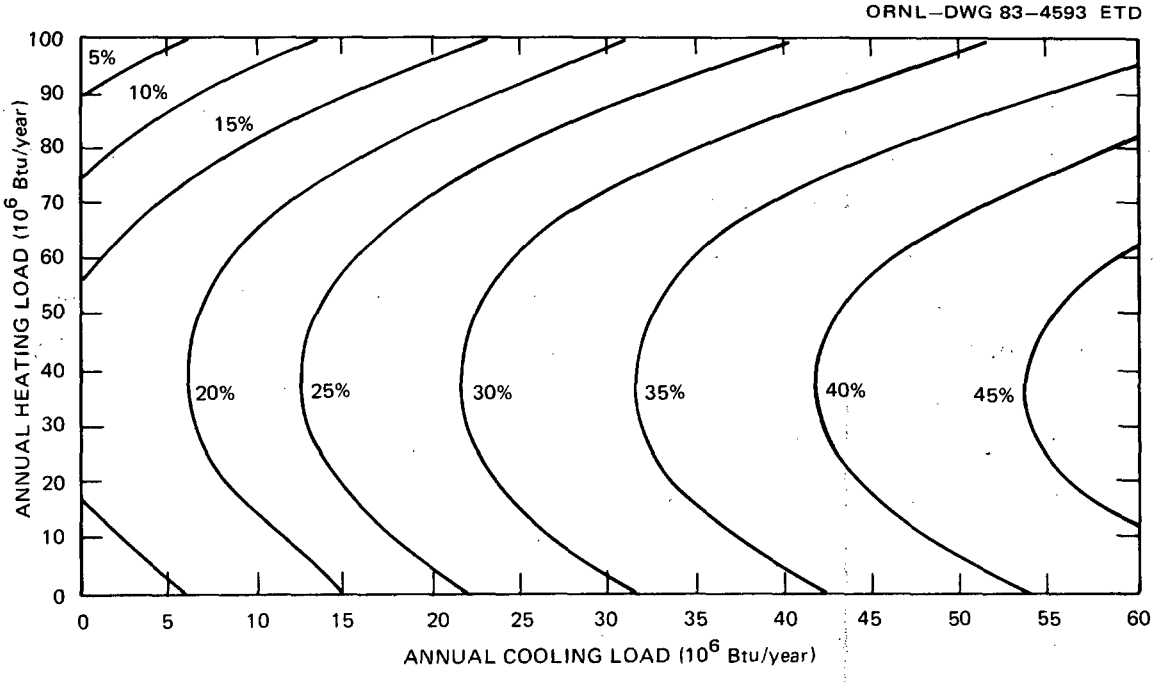

Fig. 6. Percent water heating energy savings as a function of yearly heating and cooling loads.

previous section. If additional insulation is being recommended, the loads to be used in conjunction with Fig. 6 should ideally be those that will be experienced after the insulation level is upgraded. This information would be available because an estimate of energy consumption after upgrading is made in assessing the insulation system. However, using this information would require that the model audit procedure be modified significantly to make it interactive. If the updated load information is not available, the present loads can be used. However, the accuracy of the savings may be affected.

Knowing the annual summer and winter loads, the percent savings (PS) is simply read off of the appropriate figure (Fig. 6). The water usage adjust factor (WUAF) is given by

$$\text{WUAF} = 0.0096\ (\text{HWU}) + 0.28\ , \qquad (2)$$

where HWU is the average daily hot water consumption in gallons per day. Equation (2) was derived from the results presented in Table 3. The valid

range of the expression is from 25 to 75 gal/d. The annual fractional saving is then given by multiplying PS by WUAF.

In some areas, utility rates change from summer to winter. In such a case, it is important to know the winter and summer savings so the appropriate utility rate can be applied to each. It is also necessary to determine the summer savings in those cases where the heat reclaimer is being evaluated in conjunction with a central air conditioning unit. In these instances, the fraction of total savings accrued in summer (FRAC) is read from Fig. 7. The summer fractional savings (SFS) are then given by

$$SFS = (PS)(WUAF)(FRAC) , \tag{3}$$

and the winter fractional savings (WFS) are given by

$$WFS = (PS)(WUAF)(1 - FRAC) . \tag{4}$$

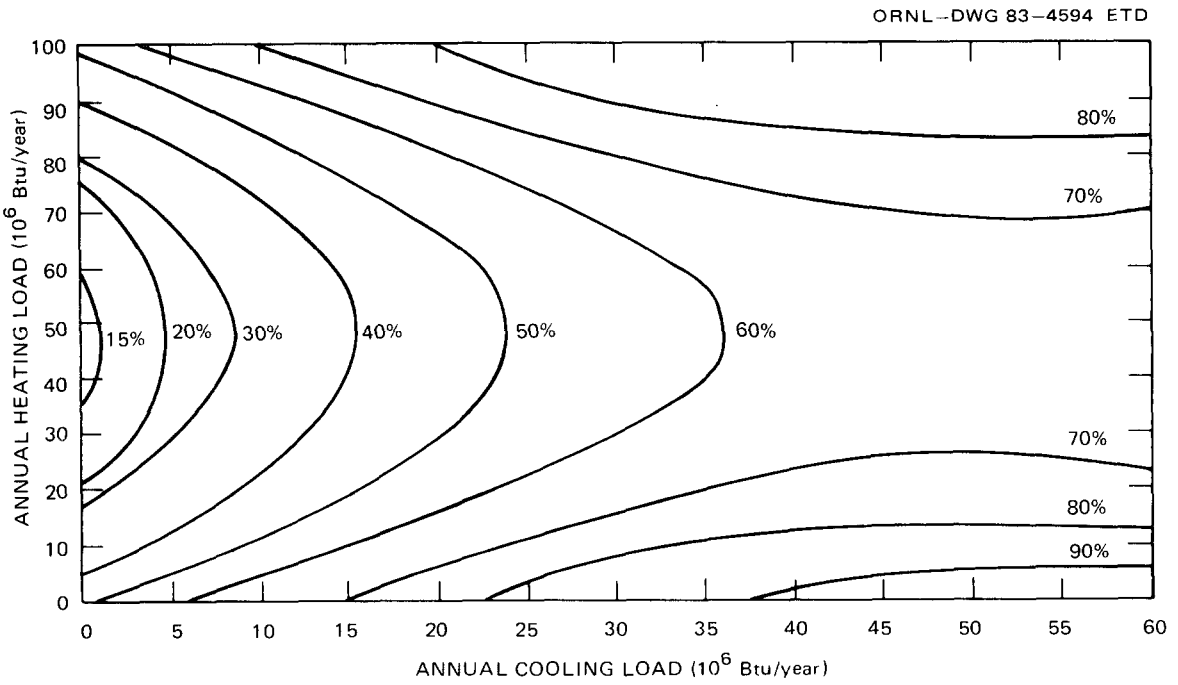

Fig. 7. Fractional water heating energy savings as a function of yearly heating and cooling loads.

The actual energy savings are calculated for each season by multiplying the appropriate fractional savings (WFS and SFS) by the estimated annual energy consumption for water heating (WHEC) as determined in the audit. For situations where only the annual energy savings (AES) are of interest, the appropriate formula is

$$AES = (PS)(WUAF)(WHEC) , \tag{5}$$

where WHS and AES are given in kilowatt hours. In cases where the summer (SES) and winter (WES) savings are required, they are given by

$$SES = (SFS)(WHEC) , \tag{6}$$

and

$$WES = (WFS)(WHEC) , \tag{7}$$

where SES, WFS, and WHEC are in kilowatt hours.

As indicated in the general procedure, the next step is to calculate the payback period. The annual monetary savings (AS) is given by

$$AS = (AES)(EC) , \tag{8}$$

where EC is the local utility rate in cents per kilowatt hour. In the situation where the summer rate differs from the winter rate, the annual savings are given by

$$AS = (SES)(SEC) + (WES)(WEC) , \tag{9}$$

where SEC and WEC are the summer and winter rates, respectively. If the heat reclaimer is to be used in conjunction with a central air conditioner, only the summer portion of this expression applies.

The payback period is then determined using

$$PB = AS/IC , \tag{10}$$

where IC is the estimated installed cost for the heat reclaimer system (including sufficient additional storage capacity to yield a total storage

capacity equal to the hot water consumption for an average day). If the resulting payback period is <7 years, installation would be recommended under current RCS rules.

As indicated by the procedure outlined in this section, realistic values for the building annual heating and cooling loads and daily hot water consumption are critical in assessing the economic viability of the heat reclaimer. Therefore, consideration of retrofit measures and lifestyle need to be properly included in the procedure. For instance, if the home has little or no insulation it is generally most cost-effective to add insulation first before considering other conservation measures. This could significantly decrease the annual heating load, thereby reducing the energy savings associated with the heat reclaimer. Therefore, it is recommended that calculations concerning the economic viability of the heat reclaimer be performed using expected heating and cooling loads after the building shell insulation is upgraded. This will require that the model audit procedure be modified to an interactive calculational scheme.

Lifestyle effects (e.g., lower indoor thermostat setting and night setback) were not explicitly examined in the analysis. However, this is not a significant limitation on the application of the assessment results because most lifestyle effects will manifest themselves in the estimation of the annual heating or cooling load. Thus, they will be accounted for in the estimation of energy savings because these values are input to the evaluation procedure.

5. SUMMARY

The heat reclaimer is a device that recovers superheat from the hot gas discharged by the heat pump compressor and delivers it to the DHW heater. During summer operation, this heat would have been exhausted to the atmosphere. Therefore, during summer months domestic water heating is performed using essentially no primary fuel. In winter the heat delivered to the hot water system would have been used for space heating. However, energy savings accrue when the heat pump operates above its balance point (above the balance point, the heat pump capacity exceeds the thermal load), because water heating is done at an enhanced COP.

Potential energy savings and economic viability of the heat reclaimer option were determined for various sites in the United States using a modified bin analysis technique. These results indicated that the heat reclaimer generally does not have a simple payback period of 7 years or less for applications where gas- or oil-fired systems are the competitor. When compared with electric resistance water heating in the 28 cities studied, energy savings ranged from about 1500 to 2800 kWh/year, and the simple payback period depended on electricity prices.

A relatively straightforward audit method has been developed for homes with electric resistance water heaters. The technical assessment results formed the basis for this development. Input to the method includes annual space heating and cooling loads and hot water energy consumption, values normally estimated in the audit procedure. The method calculates a simple payback period, which can be used by the auditor as a basis for a recommendation concerning implementation. The method has sufficient flexibility to accommodate situations where the homeowner has a central air conditioning system (as opposed to a heat pump) and where the utility summer rates differ from those in winter.

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