AN ANALYSIS OF HEAT PUMP PERFORMANCE IN SEATTLE

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ABSTRACT

The electric air-to-air heat pump has become an increasingly popular residential space conditioning system for both homeowners and utilities. The heat pump's attractiveness is associated with its reputation for high efficiency and its dual function as both a heating and cooling appliance. However, electric utilities and homeowners should be concerned with four critical attributes of heat pumps: in-situ performance, heat pump reliability, cost of heat pump systems, and effect on system loads. This paper addresses these four attributes through an analysis of metered data from 20 residential heat pump installations in Seattle and a survey of heat pump reliability and repair costs based upon vendor service records.

Analysis of in-situ performance determined that actual average heat pump heating efficiency for the monitored sites was 6.5 BTU/KWh. This efficiency is remarkably close to their ARI performance ratings. In-situ performance was assessed through a three-stage process of analyzing hourly metered data on heat pump energy use, estimating loads through calibrated thermal simulations, and developing a catalogue of HSPFs and COPs to summarize performance as a function of outdoor temperature.

Heat pump reliability and service costs were assessed through an analysis of over 980 vendor service records and a review of secondary data sources. Highlights of the survey indicate that the mean heat pump service life in Seattle is 16 years while mean compressor service life is 13.5 years. In addition, reliability has increased dramatically between 1970s and 1980s vintage heat pumps with seven-year cumulative repair costs dropping to $164 from $389.

The final component of the research was to examine total heating costs of heat pumps versus alternative residential heating equipment in Seattle. Total heating costs include the equipment purchase costs, fuel costs, and maintenance costs. In order to account for the different equipment lifetimes, the total cost was levelized over the life of the heating appliance using a 20% discount rate. The heat pump ($1,929/year)is competitive with electric furnaces ($2,081/year) but more expensive than oil and gas furnaces ($1,61/year and $1,118/year respectively). Despite the higher costs for the heat pump compared to gas and oil furnaces, the heat pump is still considered competitive since it also provides a cooling function.

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BACKGROUND

Seattle City Light initiated a study of heat pump performance and reliability in order to assess the heat pump's potential as a conservation resource.[1] This assessment is based upon three critical factors: heat pump performance, performance under frosting conditions, and heat pump reliability. In addition heat pump economics were investigated to compare heat pump costs with other commonly used residential heating systems and the costs of acquiring energy savings from heat pumps relative to other resources in the Seattle City Light's Strategic Resources Plan.

Seattle City Light (SCL) estimates that there are currently 2,800 residential heat pumps in the SCL service area and the number is projected to increase to 6885 in 2005. Although the projected 150 percent increase in heat pump installations is dramatic, it follows the nation-wide trend of heat pump shipments and the selection of heat pumps for new residential construction. Heat pumps are practical for Seattle's temperate climate of approximately 5000 heating degree days, despite the problems of incidence of frosting conditions and Seattle's relatively low cooling requirements.

This paper summarizes the study results. The first section summarizes the methodology for assessing heat pump performance followed by a discussion of the results. The second section reviews the methodology for assessing heat pump reliability and repair costs along with the related results.

HEAT PUMP PERFORMANCE ASSESSMENT

Study Methodology

SCL monitored twenty residential heat pump sites over the period of January 1983 through April 1984 and collected three channels of fifteen minute energy consumption data: whole house electric consumption, heat pump compressor and fan energy consumption, and heat pump auxiliary electric resistance heating energy consumption. These data were collected in conjunction with a 1983 Residential Heat Pump Survey -- a mail survey designed to collect information on household characteristics, heating equipment operation schedules, and appliance characteristics. In addition, SCL completed

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[1]This research was completed under the direction and support of Ted Elmer, Power Supply & Planning Division, Seattle City Light. The complete study is reported in *An Analysis Of Heat Pump Performance and Relibability In The Seattle City Light Service Area.*

new audits of the buildings in the summer of 1986 to collect data required for detailed simulation of the building sites.

The principal analytic challenge of this project was to develop a reasonable estimate of heat pump performance in the absence of measurements of thermal loads or the heat pump's output. The estimates of loads was made through a three step process.

- Calibrated hourly energy simulations for each of the twenty sites were developed using ADM-2, an hourly building thermal simulation tool.
- Hourly building loads developed from the simulations for each site were merged with the metered data to develop estimates of the heat pump's performance, including the heating seasonal performance factor (HSPF) and the heating coefficient of performance (COP).
- An average heat pump performance curve was developed from the each of the metered sites and an aggregate heat pump performance was used to calculate average heat pump performance for a typical weather year.

The study was complicated by the existence of fossil fuel back-up and wood stove heating in some of the houses. Since alternative heat sources were not monitored it was difficult to develop calibrated simulations and estimate heat pump performance. Therefore, calculations of the HSPF and COPs was divided into three parts: sites with no other backup heating (14 sites), sites with oil backup heating (2 sites), and sites with wood stoves (4 sites).

In order to be accurate, it is necessary to define the HSPF and COP measurement in the context of this paper. The HSPF, equation 1, is the ratio of the heating load delivered by the heat pump, including backup heating, divided by the electric energy used by the heat pump (also including backup heating). The coefficient of performance, equation 2, is a dimensionless measure which excludes the contribution of the backup heating in both the estimates of heating load provided and electric energy consumed. It should be noted that the calculation of the HSPF and COP were consistent with the functional form of those measures, however, the measurements were not based upon the standard test conditions as defined by DOE test procedures (HSPF) and ARI test procedures (COP). Within the context of this report, both measures are based upon hourly energy consumption and load simulation data that have been aggregated up to temperature and time bins.

Eqn 1. $$\text{HSPF} = \frac{\text{total heat provided for the season (BTU)}}{\text{total heating energy consumed for the season (watts)}}$$

$$\text{Eqn 2.}\quad COP = \frac{\text{heat provided by the heat pump}}{\text{energy consumed by the heat pump}}$$

The calibrated simulations, used to calculate the numerator in equations 1 and 2, were developed from detailed audits of each site and the occupancy surveys. Dry bulb, wet bulb, wind direction, wind speed, and cloud cover weather data from the SEATAC airport were used to make a weather file. Unfortunately, solar data were not collected so it was estimated using regression equations of solar insolation as a function of time-of-day, season, temperature, and cloud cover. Schedules for internal loads were calculated from the difference of total house electric use and heat pump energy use. Household schedules for indoor temperature settings were adjusted to calibrate the simulations so that the modelled heating balance point of the house and the maximum heating load matched the metered data.

Performance Summary

An assessment of heat pump performance was developed at two levels. First, the calibrated simulations were used to develop site-specific estimates of heat pump performance as a function of outdoor dry bulb temperature and time of day. Outdoor temperatures were grouped in 5 degree bins, and the time of day was grouped into three bins: nighttime, early morning/evening, and daytime. The hour bins were developed to estimate variations in occupancy that were not captured by correctly modelling schedules. These results were used to create site specific performance curves. The second part of the assessment developed an average performance curve and examined heat pump performance under typical weather year conditions.

Site-Specific Performance. Thermal loads from the building simulations and measurements of heat pump and backup heating were used to calculate performance measurements for each site and temperature/ hour bin. Due to space constraints, only the summary for sites with electric backup heating, or no backup heat source, are presented in Table I. Review of Table I and the comparable tables for sites with fossil fuel back-up heat or wood stoves (not included due to space constraints) led to four general observations.

- The HSPF changes significantly over the temperature bins within a given site indicating the difficulty of matching simulations (uniform occupancy habits) and actual day-to-day occupancy patterns.

- The HSPF varies dramatically across hour bins for a given temperature bin suggesting that the occupancy effects and consequent heat pump operation was not completely captured by the simulation.

- The HSPF varies dramatically across sites for a given temperature and hour bin suggesting that the variations are more influenced by the occupancy patterns and modelling of the simulated loads than actual in-situ differences in performance.

- The HSPF calculations tend to appear too low at higher temperatures, above 55° F. This may be the result of problems of simulating the houses near their balance points, and accounting for the use of natural ventilation.

Since heat pump output was not measured, it is important to consider the effect of errors in the estimation of building loads on heat pump performance estimates. Errors in measurement of energy use are also important. However, the meters were probably accurate to within 2% so those errors are probably small compared to the former errors. Errors in estimating loads are often as high as 20%.[2] An estimate of the errors in modeling loads is that a 5° shift in balance point can produce up to 10% changes in the HSPF and a 1° increase in internal temperature translates into a 1% loss in COP.[3]

The range of experimental evidence on the variation in HSPF associated with the mitigating aspects of the study design makes it difficult to differentiate between signal and noise in the data. Based upon the average HSPF for most of the heat pumps, variations in the HSPF due to field operation, and the variation in HSPF over temperature, one might expect to see the HSPF's ranging from 4 - 10. One would not expect the HSPF to drop much below 3.14, representing an efficiency of 1, although a calculated HSPF of less than 3.14 is possible in the metered data if the heat pump is not operating correctly, or if there are sufficient duct losses to unconditioned spaces.[4] In summary, many of the estimated HSPFs are within the expected range and most of the sites show the expected relationship of HSPF first increasing in temperature, and then decreasing in warmer temperatures.

Overall Heat Pump Performance. Average heat pump performance curves for the all electric sites are shown in Figure 1. The performance curves for the HSPF and COP are broken down into the three time periods and five degree bins used in the study. The rise in performance as the temperature nears freezing and the drop as the outdoor temperature rises above 45°F conforms with trends found in other, more extensive, heat pump metering

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[2]This error estimate is only an approximation based upon experience with using simulation models and reported in technical documents. (See <u>Summary and Evaluation of Field Performance Data On Unitary Heat Pumps</u>. p 6-9.

[3]<u>Summary and Evaluation Of Field Performance Data On Unitary Heat Pumps</u>, III-8.

[4]Remember that the estimation of heat pump output is the building load from the simulation. If heat pump output is lost to unconditioned spaces, then the heat pump will have to produce more heat than what is required to meet the building's heating load.

projects. The drop-off in average efficiency at warmer temperature is due to the cycling losses associated with the heat pump's intermittent operation.

The catalog of HSPFs shown in Table I was applied to the average hourly heating loads of the twenty sites for a typical weather year to develop a single seasonal performance rating. The resulting average HSPF, representing average seasonal performance for all the heat pumps under typical weather year conditions, was 6.52 BTU/KWh. This number is remarkably close to the ARI performance ratings for the heat pumps. The heat pump performance curve developed from Figure 1 was used with Seattle TMY weather to develop a single assessment of heat pump performance. This is shown in Figure II where the energy provided is shown as the sum of electric resistance heat input, compressor/fan electric input, and free heat. The third component represents the energy saved by the heat pump's ability to extract energy from the outside air. The sum of these three bars represent the electric energy that would be consumed if an electric furnace were used.

Performance Under Frosting Conditions. One of the goals of the study was to investigate heat pump performance under rapid and incipient outdoor coil frosting conditions. These conditions are of concern to SCL due to the known efficiency losses associated with heat pump defrosting and the high incidence of frosting conditions in Seattle. The metered data were analyzed to investigate observable changes in heat pump performance between no-frost, rapid-frost, and incipient-frosting conditions. Unfortunately, no significant observable affects were noted.

The most important conclusion to be drawn from this data is the *lack of significant* differences between the frosting categories. While average HSPF's in off-peak hours do exhibit the expected performance penalty under frosting conditions, these differences are statistically insignificant. Furthermore, the performance factors during peak hours show no discernable patterns. Several causes for this result, include:

- Performance measurements were constructed using hourly data and heat pump defrost cycles typically operate for approximately three to ten minutes every ninety minutes. Consequently, hourly data will tend to obscure the amount of energy used in defrost periods.

- Confidence in the estimates of the HSPF's and average COP's decreases as the number of hours used to construct the estimates decreases. When subsetting the data to the extent required to examine frosting conditions, the cell sizes of some temperature bins and hour bins becomes extremely small.

- The estimates could be "swamped" by other factors that are causing fundamental differences in HSPF's which are not being controlled for. While the estimates do control for dry bulb temperature, time of day, and dew point depression, they do not control for the effects of occupant behavior, which may vary significantly within these estimates.

HEAT PUMP RELIABILITY AND COST ASSESSMENT

Heat pumps have a reputation for being expensive to purchase and unreliable and hence expensive to operate. Since economic performance is as important as energy performance in the assessment of the heat pump's value as a conservation resource, the second objective of the study was to develop quantitative estimates for heat pump reliability and repair costs. The assessment methodology and study results are reviewed in this section.

Methodology For Study Of Heat Pump Reliability

Heat pump reliability data were developed from two sources: a review of other reliability and repair cost studies in other regions of the country and a survey of heat pump vendors/contractors in the greater metropolitan Seattle area. The heat pump vintages were divided into two segments due to the widely accepted notion that heat pumps in the 1980s incorporated significant changes making them more reliable. Repair cost were collected in conjunction with the incidence of repairs and were used to develop profiles of average heat pump repair costs and heat pump component repair costs. The survey resulted in examination of 981 repair records for 190 heat pump installations in the metropolitan Seattle area. These records were randomly selected from five local heat pump contractors. In addition 50% of the local vendors were sampled, with 16 responses, and were asked to complete a telephone survey on heat pump maintenance and heating equipment costs.

The local survey data were supplemented by data from six studies in the U.S. and Canada on heat pump reliability and repair costs. These other studies were primarily used to confirm the local survey results. (These sources are included in the references.)

Summary Of Survey

The resulting aggregation of data were used to develop an overall profile of heat pump reliability based upon heat pump age for the 1970s and 1980s era heat pumps and also a profile of major component failures.

The local survey and other studies reveal the following composite characterization of heat pumps.

- The mean heat pump service life is 16 years, while the mean compressor life 13.5 years.
- The seven year average cumulative repair costs for 1980s vintage heat pumps in Seattle was $164, compared to $389 for the 1970s vintage heat pumps, a *240% improvement*. The annual average cost per unit was $56/year for the 1970s vintage, compared to $23/year for the 1980s era heat pumps. This indicates that heat pumps

have become more reliable with resulting lower repair costs. This trend is also reflected in other studies in the U.S.

- The overall reliability of heat pumps will continue to increase due to increased penetration and improvement of solid state controls and introduction of variable speed compressors.

Reliability and Repair Costs

An analysis of the probability of heat pump failure by heat pump age was completed for each vintage, and the results are shown in Figure 3. The analysis shows that both the 1970 and 1980 vintages have a high probability of failure in their first year of operation (.67 - .73). Problems in the first year range from small problems such as replacing wiring, adjusting controls, and repairing leaks, to major problems including compressor replacement. It is interesting to note that almost half of all compressor replacements occur in the heat pump's first year. These replacements are usually covered by manufactured warrantee and thus are at no cost to the consumer. (A compressor replacement out of warrantee had an average cost of $924.56.

The probability of heat pump failure decreases rapidly subsequent to the first year of operation and then starts to rise in the fifth year. However, the 1980s vintage heat pumps have a lower failure rate after year 5. The probability of repair continues to rise through the seventh year for 1970 vintage heat pumps while it drops after year for five for the 1980 vintage heat pumps. The heat pumps components accounting for the highest percent of failures are: compressor components (22.6%), defrost controls (19.2%), indoor unit (16.6%), and the outdoor unit (15.3%). Compressor repairs covered a range of subcomponent problems including the start and run capacitors, run delays, transformers, crank case heater, and the accumulator. The second most common problem, defrost controls, typically involved the timer or the low pressure of the refrigerant. The distribution of component failures and their relative repair costs is shown in Figure 4.

Cost Comparisons

Repair costs of heat pumps versus other heating systems was examined to assess the heat pump's benefit from the consumer's perspective. This comparison is difficult to make since the heat pumps provides a cooling capability which is valuable to the customer. The survey of Seattle heat pump vendors/contractors noted that most of their heat pump customers also use the heat pump for cooling. Therefore, life cycle cost analysis should consider the cost of a air conditioning system. Cost estimates for heating system acquisition and installation were developed from two sources: secondary sources including <u>Means' Mechanical Cost Data 1986</u> and data from other studies, and a survey of Seattle area vendors.

Installation costs from different sources were difficult to compare due to differences in what is being estimated. For example, the Mean's Construction Cost data had lower estimates than the Seattle contractors. While the Mean's estimates do not include plumbing and installing flues, the local vendor estimates include all the details associated with installing the equipment, including flues. Therefore, local contractor estimates were viewed as more indicative of the true total cost that the residential homeowner would face. Since cost estimates depend upon the heating unit's capacity, efficiency, and whether it is a retrofit or new installation, a range of estimates were collected.

Maintenance costs and service life information for each of the equipment types were also collected from the local vendor surveys and compared with estimates from secondary sources. Maintenance costs are separated into three time spans: the first five years, years 6 - 10, and years 11 - 15. A summary of the installation costs and maintenance costs are shown in Table II. Installation costs for retrofit applications do not include the cost of ductwork.

Table II: Local heating equipment costs - from vendor surveys.

Equipment	Size	Effic.	Capital Cost	Installation New	Installation Retro	Annual Main. 5	Annual Main. 10	Annual Main. 15	Serv. Life
Convent. gas	57MBH	80	852	1700	342	35	45	47	19
Convent. gas	103MBH	80	1011	2287	468	33	41	43	19
Condense gas	60MBH	91	1498	2650	483	96	149	165	-
Condense gas	100MBH	91	1603	2890	500	80	109	113	-
Oil furnace	67MBH	74	1019	1567	240	70	70	70	22
Oil furnace	106MBH	80	1125	1967	265	70	70	70	22
Elec furnace	20KW	100	607	1533	317	31	42	44	20
Elec furnace	39KW	100	770	1918	344	41	53	57	20
Heat pump	3.0TON	6.8	2864	1900	700	95	147	162	14
Heat pump	3.2TON	7.8	3688	2359	1129	100	155	170	14
Heat pump	4.7TON	6.8	3900	2850	750	105	159	175	14
Heat pump	4.5TON	7.3	4236	2560	1280	110	170	187	14

Total System Costs

Comparable purchase and installation costs for residential heating systems in Seattle along with annual maintenance costs were collected for heat pumps, gas furnaces, and oil furnaces. The combination of the average residential heating loads, relative equipment efficiencies, and system costs allow the utility to develop comparative cost estimates for the different heating systems.

A cost model developed with spreadsheet software allows the user to adjust costs and compare the different heating equipment with alternative costs and assumptions. A sample of the model output, using current fuel prices for Seattle, is provided in Table III. The model shows that the heat pump is competitive with electric resistance heating. While annual levelized costs of the heat pump are over $800 more than the cheapest system, the conventional gas furnace, it should be recognized that the heat pump provides the added service of air conditioning in the summer.

Table III. Heat pump levelized cost model.

EQUIPMENT	SIZE	EFFIC	CAPITAL	NEW INSTALL $	MAIN COST/YEAR 5	10	15	SERV LIFE
CONVEN. FURNACE	57 MBH	80	852	1700	35	45	47	19
CONDENSING FURNACE	60 MBH	91	1498	2650	96	149	165	15
OIL FURNACE	67 MBH	74	1019	1567	70	70	70	22
ELEC FURNACE	20 KW	100	607	1533	31	42	44	20
HEAT PUMP	3 TON	6.8	2864	1900	95	147	162	16
HEAT PUMP	3.2 TON	7.8	3688	2359	100	155	175	16

MODEL PARAMETERS

ANNUAL HEAT LOAD	106402	OIL PRICE(KBTU):	0.00707
DISCOUNT RATE:	0.2	GAS PRICE (KBTU):	0.00415
		ELECTRIC PRICE:	0.05150

EQUIPMENT	CAPITAL	DISC. O&M	FUEL COST	TOTAL COST	LEVELIZED COST
CONVEN. FURNACE	$2,552	$189	$2,673	$5,415	$1,118
CONDENSING FURNACE	$4,148	$546	$2,269	$6,963	$1,489
OIL FURNACE	$2,586	$344	$4,991	$7,920	$1,613
ELEC FURNACE	$2,140	$173	$7,818	$10,131	$2,081
HEAT PUMP	$4,764	$548	$3,811	$9,123	$1,929
HEAT PUMP	$6,047	$579	$3,323	$9,949	$2,104

SUMMARY

Heat pump performance from sixteen monitored sites in Seattle was assessed from metered 15 minute energy consumption data and building loads developed from an hourly thermal simulation model. The use of an hourly simulation model to estimate loads for heat pump performance calculations has many shortcomings. However, the approach provide a performance estimate at a relatively low cost. In this case, the HSPF performance estimate of 6.52 KBTU/KWh was remarkably close to the ARI estimate. The average heating load for the twenty metered sites was 106,402 KBTU and estimated heat pump energy use under typical weather years was 16,317 KWH. While it was possible to develop a performance curve as a function of temperature, no discernable performance penalties were identified for heat pumps operating under frosting conditions. In addition, the difference in performance curves by time-of-day indicated that not all the occupancy affects were captured by the schedules in the thermal simulation model.

Heat pump reliability studies indicated that heat pump performance has improved significantly since the 1970 vintage heat pumps. The average service life for a heat pump in Seattle is 16 years, while the average compressor life is 13.5 years. The most common heat pump repair problems involve the compressor, followed by defrost controls. The combination of higher initial and O&M costs results in the heat pump costing approximately $800/year more than the cheapest gas furnace, however the homeowner also receives cooling benefits from the heat pump.

Table I. COP SUMMARY FOR SITES WITH ELECTRIC BACKUP.

HOUR BIN	TEMP. BIN	SITE # 3293	SITE # 4065	SITE # 4412	SITE # 5026	SITE # 5392	SITE # 5592	SITE # 5856(a)	SITE # 5978	SITE # 6202	SITE # 6214	SITE # 6221	SITE # 7478	SITE # 8403	SITE # 8888
1	< 21	2.59	1.87	2.80	2.54	2.46	2.38	2.86	1.41	1.81	1.53	3.04	3.34	0.20	4.02
1	21-25	2.81	2.56	2.83	3.10	2.94	2.50	0.12	0.87	2.53	2.15	3.62	2.71	1.14	3.50
1	26-30	2.45	2.75	3.08	3.56	2.90	2.12	6.00	0.96	2.54	1.75	4.04	2.34	1.73	5.73
1	31-35	2.35	3.28	3.01	4.10	2.83	2.17	4.31	1.50	2.41	1.85	3.46	1.61	1.61	6.00
1	36-40	2.33	2.92	3.04	3.63	3.05	2.27	3.08	1.27	2.80	1.81	4.40	1.13	1.93	6.00
1	41-45	2.41	3.41	3.30	4.75	2.91	2.27	2.98	1.19	2.51	1.81	5.44	1.06	1.75	6.00
1	46-50	2.18	4.25	3.45	3.56	2.76	2.14	2.40	1.15	2.50	1.69	6.00	1.30	1.63	4.54
1	51-55	1.95	6.00	4.84	4.17	2.37	1.70	2.48	1.91	4.10	1.35	5.89	1.53	1.16	2.04
1	56-60	2.36	4.61	4.45	5.98	2.25	2.34	0.89	3.68	3.60	0.56	3.81	6.00	0.31	3.21
1	> 60	.	0.82	0.70	6.00	1.88	4.94	0.68	.	5.84	0.17	1.35	.	.	6.00
2	< 21	2.53	1.51	3.14	2.79	1.75	2.59	-13.69	1.57	1.90	1.63	3.03	3.06	1.50	2.04
2	21-25	2.57	2.68	3.33	2.89	2.45	2.35	-7.65	1.00	1.63	1.37	4.10	3.12	1.68	2.60
2	26-30	2.40	1.42	3.29	2.56	2.40	2.56	-6.21	1.32	2.34	1.64	3.95	2.59	2.17	1.67
2	31-35	2.00	2.39	3.36	2.38	2.41	2.27	-2.30	1.53	2.05	1.51	3.94	1.70	1.93	1.45
2	36-40	1.90	2.35	3.48	2.48	2.44	2.16	-1.47	1.47	1.90	1.50	2.76	1.33	2.09	1.44
2	41-45	1.57	2.40	3.33	2.01	2.22	1.85	-0.47	0.95	2.02	1.31	2.14	1.36	2.06	1.09
2	46-50	1.38	2.08	3.57	1.94	2.01	1.53	-0.31	0.82	1.96	1.16	1.38	1.79	2.06	0.95
2	51-55	1.08	1.65	4.07	1.50	1.63	1.14	-0.07	0.60	2.18	0.87	-.19	1.81	2.00	0.67
2	56-60	1.22	1.16	5.37	1.44	1.44	1.52	0.37	0.06	1.34	0.33	-.58	0.51	1.15	1.18
2	> 60	.	0.85	1.01	6.00	1.83	1.02	1.88	.	0.78	0.15	0.67	0.16	0.75	2.50
3	< 21	2.84	2.20	2.98	2.11	2.38	2.81	-5.71	1.63	0.98	1.95	2.61	3.25	1.65	3.26
3	21-25	2.62	2.73	2.53	2.60	2.25	2.79	-0.62	1.18	1.59	2.18	2.58	4.02	1.87	3.12
3	26-30	2.56	1.23	2.47	2.43	2.50	2.67	-2.66	1.21	0.95	2.20	2.92	5.31	2.75	2.69
3	31-35	2.56	3.84	3.32	2.85	2.57	2.81	0.65	1.98	1.22	2.25	3.31	1.96	2.40	2.82
3	36-40	2.43	3.52	3.09	2.93	2.36	3.07	-0.31	1.80	1.52	2.22	3.03	1.55	2.36	2.58
3	41-45	2.64	3.38	3.45	2.56	2.21	3.53	0.81	1.52	1.87	2.31	3.34	1.86	2.71	2.45
3	46-50	2.42	3.00	3.77	2.27	1.95	3.84	0.80	1.55	1.80	2.18	1.75	2.93	2.61	1.69
3	51-55	2.40	2.69	4.61	2.03	1.58	3.25	0.35	1.78	1.91	1.47	1.11	4.26	2.00	1.17
3	56-60	2.71	1.68	3.54	2.25	1.79	1.81	0.79	2.88	1.35	0.38	-.06	1.87	1.43	2.00
3	> 60	.	0.76	0.28	6.00	2.15	0.39	1.36	-.20	0.67	0.14	0.27	1.22	.	2.15

a) The negative COPs for site 5856 have no physical significance, instead they are indicative of the inability to calibrate the simulated loads to match site operating conditions.

Figure 1

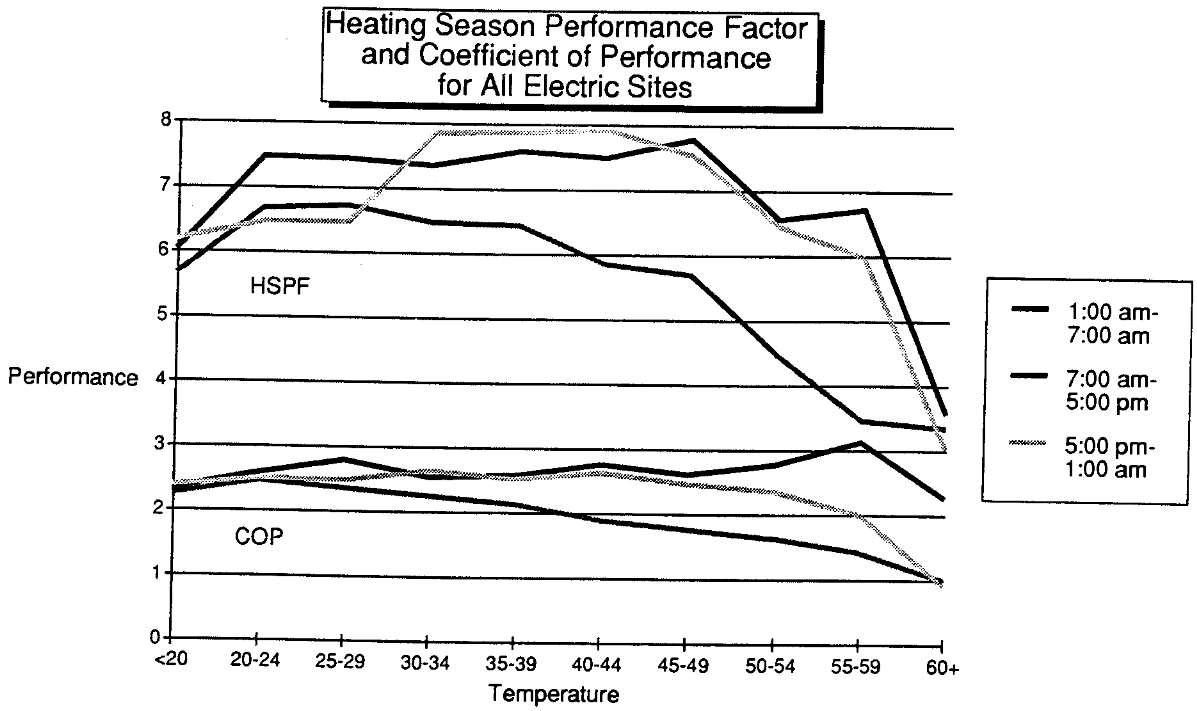

Figure 2

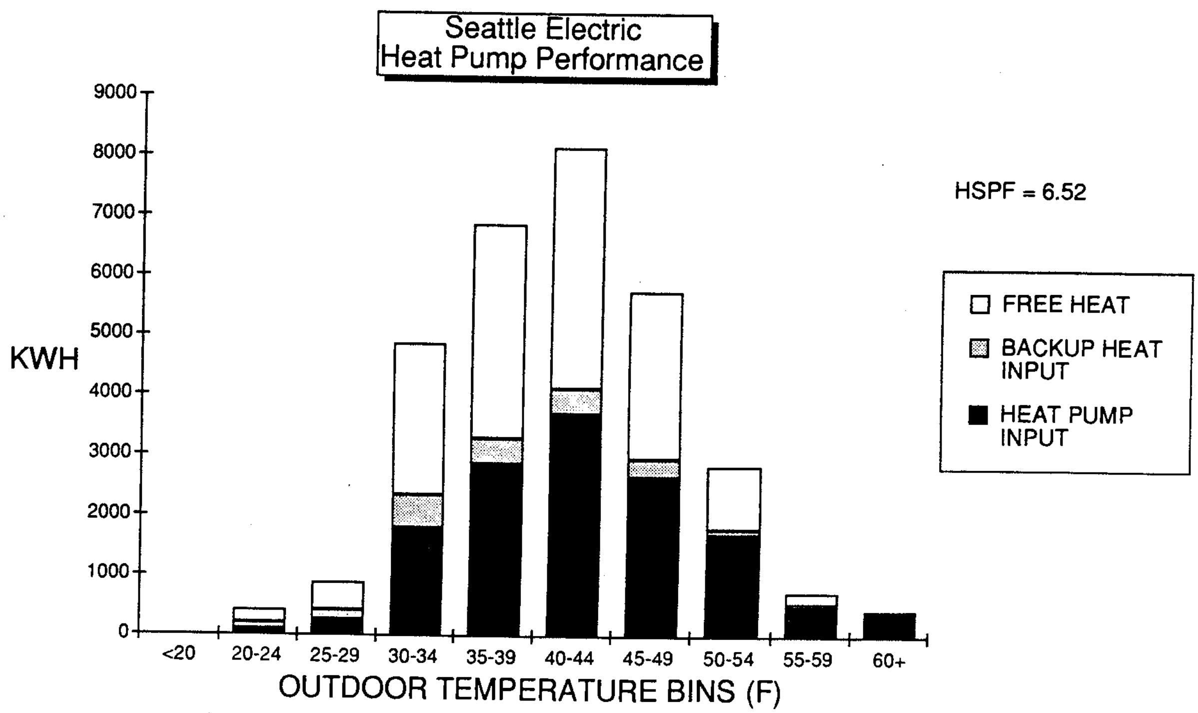

Figure 3

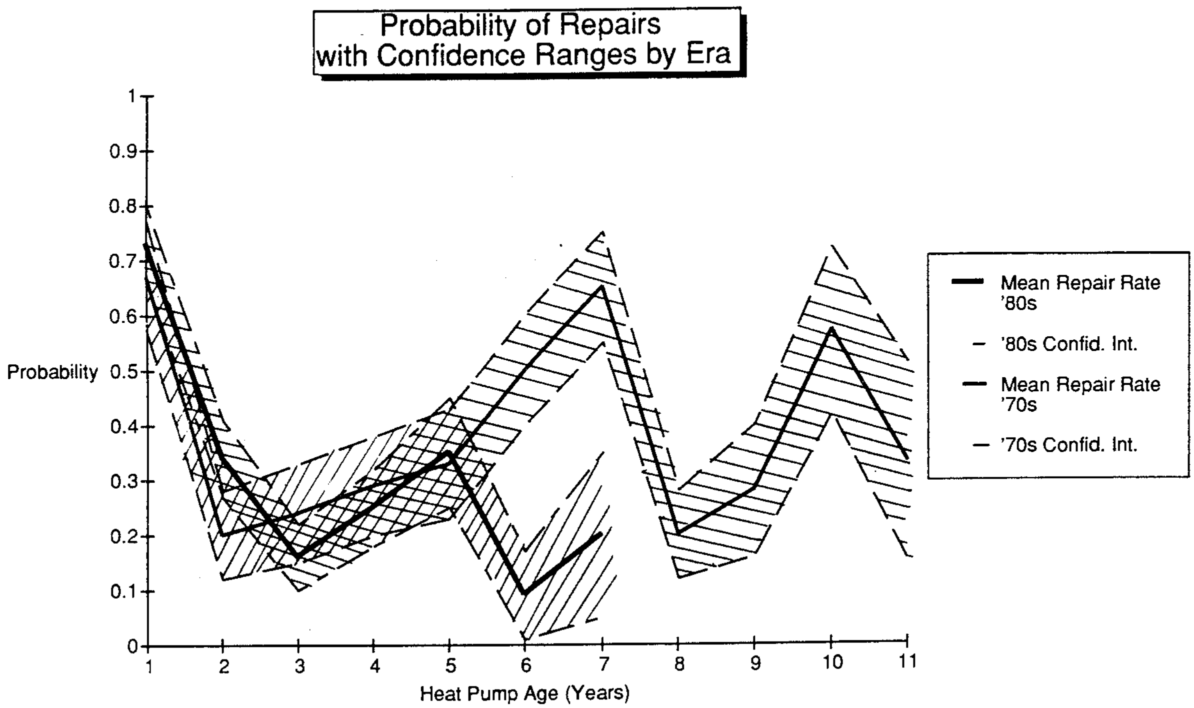

Figure 4