Field Comparison of Conventional HVAC Systems with a Residential Gas-Engine-Driven Heat Pump

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Through its Office of Federal Energy Management Program (FEMP), the U.S. Department of Energy (DOE) provides technical and administrative support to federal agency programs directed at reducing energy consumption and cost in federal buildings and facilities. One such program is the New Technology Demonstration Program (NTDP).

In this context, NTDP is a demonstration of a U.S. energy-related technology at a federal site. Through a partnership with a federal site, the utility serving the site, a manufacturer of an energy-related technology, and other organizations associated with these interests, DOE can evaluate new technologies. The partnership of these interests is secured through a Cooperative Research and Development Agreement (CRADA).

The Fort Sam Houston (San Antonio, Texas) NTDP is a field evaluation of a 3-ton gas-engine-driven residential heat pump. Details of the technical approach used in the evaluation, including instrumentation and methodology, are presented. Dynamic performance maps, based on field data, are developed for the existing residential furnaces and air conditioners at Fort Sam Houston. These maps are the basis for comparisons between the candidate and current equipment. The approach offers advantages over pre/post-measure evaluations by decoupling the measured equipment performance from the effects of different envelope characteristics, occupant behavior, and weather.

Introduction

The New Technology Demonstration Program was established by the U.S. Department of Energy in 1990. Under the auspices of DOE's Federal Energy Management Program, the New Technology Demonstration Program works to reduce federal sector energy costs and improve overall energy efficiency; introduce new energy-efficient technologies to the federal sector in a more timely manner, thereby narrowing the gap between private sector and federal deployment rates of new technologies; and create jobs in the manufacturing sector by spurring the use of new, U.S. -manufactured energy-efficient and environmentally beneficial technologies.

When first established, the New Technology Demonstration Program provided only for evaluation of new technologies at federal sites. FEMP expanded the Program in early 1994 to widen laboratory involvement and provide information about commercially available energy-efficient technologies to the federal sector. FEMP refers to these two program components as Technology Demonstration Projects and Information Transfer.

The New Technology Demonstration Project at Fort Sam Houston features a 3-ton gas-engine-driven heat pump that will be installed in a residence at the military base in Spring 1994. The heat pump (Harnish et al. 1991) uses a single-cylinder, four-stroke, 5-hp engine fueled by natural gas. Distinctive features include an inherent load-matching capability. By varying engine speed, the unit can be dynamically controlled to provide capacity balanced with thermal loads. This reduces cycling and the associated thermal losses and equipment wear. The unit also produces added heating capacity through engine heat recovery.

The goal of the evaluation is to measure the installed field performance of the candidate unit and compare it to that of the existing HVAC equipment in the residences at the base. The thermal measurements and maintenance records will be primary elements in life cycle cost analysis of potential savings from the candidate unit. This paper describes the methods to be used in the comparison and focuses on the development of performance maps for the existing equipment. The performance maps are derived from baseline field measurements on a pulse-combustion furnace and an air conditioner during the period of 8/93 to 2/94.

Methodology

Ideally, a performance comparison of two HVAC units is done side by side under identical operating conditions. While this can be achieved under steady-state testing in the laboratory, dynamic field conditions in houses with occupants are difficult to control to give equivalent side-by-side conditions. A pre/post assessment approach offers some advantages in that the house and possibly the occupants remain the same during the two phases of the test. However, changes in weather and occupant behavior lead to changes in operating conditions and equipment loading that can be addressed only partially with weather normalization techniques. To address these potential problems, a hybrid approach is taken. The approach includes: (1) weather normalized pre/post comparison of energy usage, (2) a side-by-side comparison of seasonal coefficients of performance (COPS), and (3) performance mapping of the existing units followed by a projection of their maps onto the load records from the installed candidate unit.

A performance map is a form of empirical model that is used to predict a system's (unit and thermostat) response to a time series of load and operating conditions. The loads and conditions recorded from monitoring the candidate unit drive the performance maps of the existing unit. The result is a prediction of the existing units' energy usage under the conditions and loads of the candidate unit. Performance mapping offers advantages over the pre/post and side-by-side comparisons in that changes in weather, loading, and operating conditions are addressed. The key component of the map is a regression-based characterization of part-load performance.

Maps should be capable of projecting to a wide range of operating and loading conditions. With air conditioners, where capacity depends on ambient conditions, this capability can be achieved through mapping relative to manufacturers' steady-state performance data. Doing so minimizes the need for a broad range of baseline conditions. Essentially, the ratio of the measured sensible capacity to a fit of the manufacturer's steady-state sensible capacity data is correlated with the duty cycle. Duty cycle is defined as the blower fractional on-time during a cycle relative to the sum of the on-time and the prior off-time. With the furnace, the capacity is not strongly dependent on operating conditions; therefore, the capacity map is absolute and only a function of a duty cycle. Equation (1) shows the functional form of the air-conditioner maps. Equation (2) shows the form for the furnace.

$$
\begin{aligned}
C &= C_{ss}(T_{odb}, T_{idb}, T_{iwb}, \dot{V})\ C_{pl}(x) \\
P &= P_{ss}(T_{odb}, T_{iwb}, \dot{V})\ P_{cf}
\end{aligned}
\tag{1}
$$

where C = part-load sensible capacity [Btu/h]
C_{ss} = manufacturer's steady-state sensible capacity [Btu/h]
C_{pl} = air-conditioner part-load factor (function of duty cycle)
x = duty cycle
T_{odb} = outdoor dry-bulb temperature [°F]
T_{idb} = indoor dry-bulb temperature [°F]
T_{iwb} = indoor wet-bulb temperature [°F]
$\dot{V}$ = volumetric flow rate of evaporator fan [cfm]
P = compressor power consumption [kW]
P_{ss} = manufacturer's steady-state data on compressor power [kW]
P_{cf} = empirically-based correction factor to P_{ss}

$$
\begin{aligned}
H &= H_{ss} H_{pl}(x) \\
G &= G(t)
\end{aligned}
\tag{2}
$$

where H = part-load furnace capacity [Btu/h]
H_{ss} = full-load field capacity [Btu/h]
H_{pl} = furnace part-load factor (function of duty cycle)
x = duty cycle
G = gas consumed by furnace (ft^3)
t = supply fan run time (h)

The maps are implemented through use of a time-series record of load and conditions in which the candidate unit runs. For each time increment in the series, the capacity equations are solved to determine what run time (duty cycle) is necessary to satisfy the load at the recorded conditions. The equations are solved through iteration because the capacity calculation is dependent on the part-load functions, which are nonlinear with respect to duty cycle and make closed form solutions unavailable. If the estimate of run time is smaller than minimum run times seen during periods of low load (from the baseline data), the load is not acted on but added to the next period. This keeps the simulation from artificially low loading. This run-time threshold can be established by comparing the map against its own baseline load record and requiring that the map's estimate of energy consumption equal the energy total in the baseline data.

With run time estimated, the compressor's energy consumption is calculated from an empirically-based correction to a fit of the manufacturer's data on compressor power draw [P in Equation (l)]. The energy usage from the condenser fan and supply fan is calculated from average field-measured power draw. For the furnace, gas consumption is determined using an empirical relationship between gas volume usage and run time [G in Equation (2)].

Three test houses at the Fort were chosen to support the hybrid approach. The houses have identical structural design and solar exposure and are occupied by families with one or two children. Energy records were checked to see that the houses are typical of other similar houses at the Fort and that the existing HVAC systems have capacities similar to the 3-ton candidate unit. In each house, the system is installed in the basement. Two of the houses currently have HVAC systems that represent the best available at the Fort. This includes pulse-combustion furnaces and air conditioners with scroll compressors. A third house represents the worst case, with the oldest of the Fort's conventional air conditioners and furnaces.

These HVAC systems bracket the range of equipment performance currently at the Fort. Baseline data collection (begun in August 1993) continued in one of the best-case houses until the new gas-engine-driven heat pump was installed in Spring of 1994. Data collection then continues for another year on all three houses. This will allow pre/post comparison between the best case and the candidate in the installation house, mapping from all three base units to the candidate load and conditions record, and side-by-side seasonal COP comparisons between the candidate and the two equipment extremes from the base.

Instrumentation

Baseline monitoring in support of the hybrid assessment approach involved measurements of system outputs (capacity), system inputs (energy consumption), and operating conditions. Data loggers at the site produced a record of measurements at 15-minute intervals. The records were downloaded daily to a computer in Richland, Washington, for storage and analysis. All measurements in the air stream (return-air psychometric and sensible capacity) are conditionally sampled to produce an average over periods of output (supply fan is on). Measurements of conditions outside of the air stream, such as conditioned space, basement, and outdoor condenser temperatures, are based on continuous sampling over the entire 15-minute logger period. All averages are based on 5-second sampling intervals.

Operating conditions are characterized by temperature measurements in the return air stream, in the basement, and outside (sun-shielded) near the condenser. Platinum resistance temperature devices (RTDs) are used for the absolute temperature measurements. Humidity in the return air stream is measured with solid-state polymer film sensors calibrated using saturated salt solutions.

Sensible capacity (differential temperature) is measured with a 24-gauge type-T thermopile using 6 junction pairs. Six junctions are placed upstream of the furnace filter on a single support rod followed by six junctions downstream of the evaporator coils on two support rods (Figure 1). Volumetric flow rate of the supply air-handler is determined with a heat injection test using a 5-kW heating coil commonly used as a back-up heat source for heat pump systems. Flow rate is determined for the high-speed blower mode associated with air-conditioner operation and also the low-speed blower mode associated with furnace operation. Latent capacity (condensate flow) is recorded by counting contact closures from a calibrated tipping bucket rain gauge. Supply fan speed (in RPM) is recorded with an optical sensor that counts the passes of a piece of reflective tape attached to the far side of the fan rotor. Cycling data is recorded as a count of the times the supply fan turns on during the 15-minute logger period.

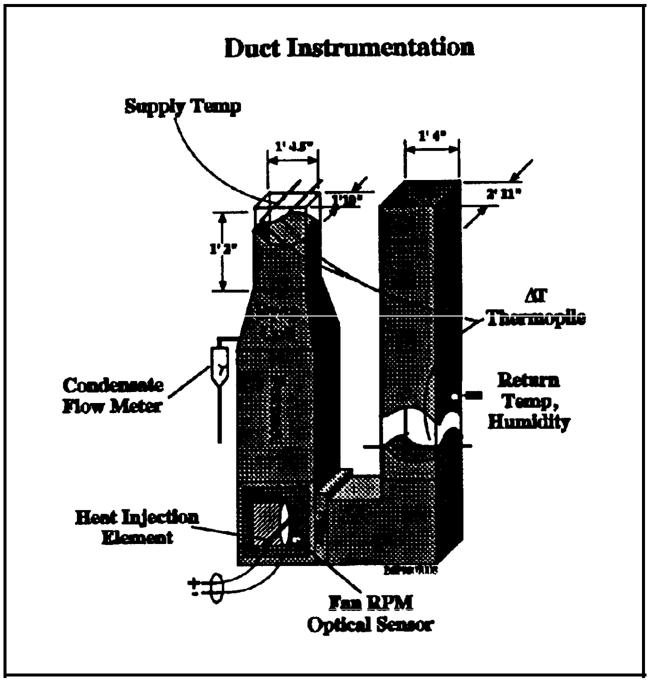

Figure 1. Instrumentation Used in Measuring Output Capacity

Electric energy use is measured with current transformers at the compressor, condenser fan, and supply fan. Contact closures from a reed switch on an inline gas meter are counted to record volumetric flow of natural gas to the furnace.

When the gas-engine heat pump was installed in Spring 1994, the monitoring instrumentation was changed to accommodate the variable airflow characteristics of the unit. With changing flow rates, independent averages of ΔT and $\dot{V}$ do not properly represent the changing capacity. Instead, the product, $\dot{V}\Delta T$, must be averaged over the period the supply fan runs. This requires a real-time multiplication capability in the data logger and also a real-time volumetric flow rate measurement. The new logger is a PC-based system with conditional sampling capabilities and real-time cross-channel math processing. A laboratory-based correlation along with a site calibration is used to determine V from fan power and rpm data.

Analysis

Sensible and latent capacity are calculated with Equation (3) (ASHRAE 1989). In the sensible calculation, it is assumed that the supply air fan runs at a constant speed and provides approximately constant volumetric flow. In other words, the fan by design provides constant volumetric flow; it is assumed that neither accumulation of dust in the furnace filter nor possible changes in the outlet dampers by the occupants will affect it. The corresponding mass flow was calculated using a psychometric routine for specific volume, which included corrections for barometric pressure, temperature, and moisture. Pressure data was not available from the site sensors but was integrated from an online public database (on the Internet) of hourly San Antonio weather from the National Climatic Data Center (NCDC). These sea-level referenced pressures where then corrected for site elevation.

The field-measured latent capacity is not used directly in the mapping process. This is because the maps project sensible capacity onto thermostat-driven sensible load records. However, the latent capacity will be used directly in the side-by-side comparison of seasonal COP. Caution is needed when using condensate flow to estimate latent capacity: the condensate storage capacity in the fin and collection pan causes a fill/drain pattern that delays the condensate flow record from the time that water is actually removed from the air stream. Simple fin/pan storage models can be used to interpret condensate flow data records (Miller 1984). The manufacturer’s sensible/total (S/T) ratios are used in developing C_{ss} in Equation (l). To check these steady-state S/T ratios, the seasonal condensate total, as projected from the manufacturer’s data for sensible/total ratios, was compared with the field sensible capacity and condensate seasonal total. The manufacturer’s S/T ratio data was, on average, 2.4% higher than what would be needed to predict condensate levels equal to the measured total.

$$\begin{aligned} S &= 60\ \dot{V}\ \Delta T\ \rho(\ P_b, T_{idb}, T_{iwb})\ c_p \\ c_p &= 0.24 + 0.444W \\ L &= \dot{m}_{cond}(h_g(T_{idb}) - h_{cond}) \\ h_g &= 1061 + 0.444T_{idb} \end{aligned} \tag{3}$$

where S = sensible cooling capacity [Btu/h]
$\dot{V}$ = supply air flow rate [cfm]
ΔT = temperature differential across evaporator coils [“F]
ρ = air density [lb air/ ft^3]
P_b = barometric pressure [in. Hg]
c_p = specific heat of air [Btu/lbm °F]
L = latent cooling capacity [Btu/h]
$\dot{m}$ = condensate flow rate [lb/h]
h_g = specific enthalpy of saturated water vapor [Btu/lbm water]
h_{cond} = specific enthalpy of condensate at 50°F [Btu/lbm water]

The efficiency of the furnace was calculated using natural gas heating values as shown in Equation (4) where the factor 1000 Btu/ft^3 is the value assumed for standard conditions (ASHRAE 1989). This equation is used with the gas meter’s volumetric flow records to account for variations in density from pressure and temperature. The house gas-line temperature was estimated from an air temperature measurement in the unconditioned basement.

$$H_v = 1000 \frac{(P_{site} + \Delta P)}{P_{st}} \frac{T_{st}}{T_{line}} \tag{4}$$

where H_v = heating value of natural gas [Btu/ft^3]
P_{site} = barometric pressure at the site [in. Hg]
AP = house line pressure above atmospheric [in. Hg]
P_{st} = standard pressure, 29.921 [in. Hg]
T_{st} = standard temperature, 518.7 [°R]
T_{line} = temperature of gas in house line [°R]

In analyzing field capacity data taken from fixed-interval data loggers, consideration must be given to the relationship between the logging interval and the cycling characteristics of the equipment. Ideally, the field data logger should have the capability of recording a time stamp at the beginning and end of each HVAC event; this clearly supports mapping by duty cycle. If this is not possible, as was our case, fixed-interval logger periods must be chosen carefully so as to collect enough data to resolve the elements of each cycling event.

Figure 2 illustrates the overall pattern that results from furnace events being severed by the boundaries of the fixed-interval logger period. Gas use is shown as a function of supply fan duty fraction during 15-minute logger intervals. Duty fraction is defined here as the blower fractional on-time during a 15-minute logger period. The four distinct zones in the plot are a result of how a furnace event sequence (1) burners on, supply fan off; (2) supply fan and burners on; (3) burners off, supply fan on), falls within the boundaries of the 15-minute logger period. Points with zero gas usage are 15-minute periods where there is only a cool down (no burning). Moving clockwise around Figure 2, a few points have no fan time and some gas use (pre-burn). The left side of the parallelogram represents logger periods with varying amounts of pre-burn and burn with the supply fan, but with no cooldown period. The top side has varying fractions of the cool-down period; the points on the right side contain mostly cooldown. The hole in the middle occurs because, in this range of data, the furnace typically ran for 500 seconds before going into cool down mode.

Many of the furnace events divided by logger time boundaries can be reassembled and placed in the period where the event terminates. This is done with a logic filter that acts on the record of cycle counts, run time, and gas use. Consumption and run times are totaled; capacities are weighted by run times and then totaled. Figure 3 shows gas use data after aggregation by the digital filters.

A similar filter was applied for the air-conditioner data. However, filtering is more difficult in this case because the events have less distinctive features: namely, the fan and compressor run times differ by only an 8-second protection delay in the compressor start time. Pure shutdowns are the only air-conditioner events to get completely caught by filtering; these have a zero cycle count with a non-zero run time. Filters work best when the cycling rate is low; however, when multiple events occur in a period, or when neighboring periods have nonzero cycle counts, it is difficult to determine whether the tail of the last event is contained. In one of the three houses the air conditioner cycled at a low rate. This allowed the filters to isolate nearly all individual cycle events and construct a data record by duty cycle.

After field capacity and consumption data is collected, a final step for the mapping of the air-conditioner data is the regression of the manufacturers' data for total capacity and sensible/total ratios. Together these produce a relationship for steady-state sensible capacity [C_{ss} in Equation (1)]. Also, the manufacturers' data on compressor power was regressed to give a relationship for compressor power draw as a function of conditions [P_{ss} in Equation (l)].

Results

A plot of the furnace gas use data is shown in Figure 3 (Figures 3, 4, 5, 7, and 9 are with filtered data). As with Figure 2, a linear fit to the data shows a nearly zero intercept indicating that gas use for the furnace is nearly proportional to the fan run time. This plot illustrates the relationship referred to as G in Equation (2). Because of a logger failure during the coldest part of the winter, data is available during only periods of relatively small heating loads.

The capacity data shown in Figure 4 is similar to a plot of H in Equation (2). A key difference here is that Figure 4 is plotted against duty fraction, not duty cycle. The lack of resolution in the baseline data stream prevented event isolation needed to calculate duty cycle. Figure 5 indicates efficiencies ranging from 60% at a 0.6 duty fraction to 85% at a 0.8 duty fraction. Outliers in the plots are generally severed furnace events that are missed by the logic filter.

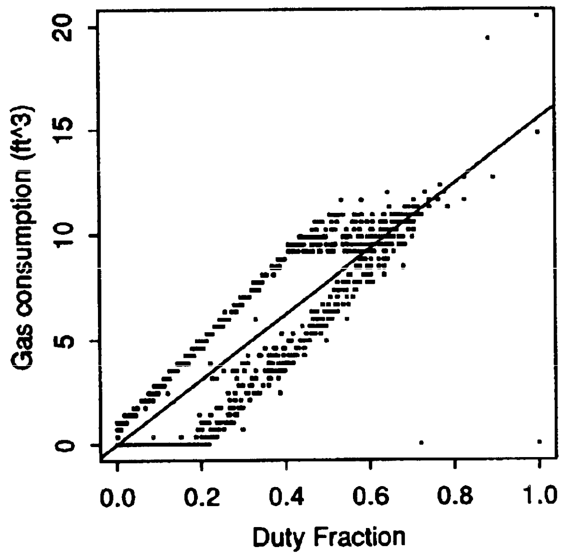

Figure 2. Unfiltered Data Illustrating Sampling Anomaly

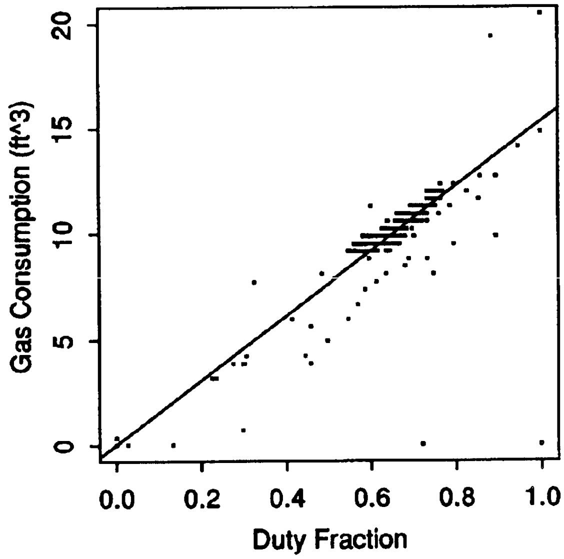

Figure 3. Furnace Gas Consumption Map (Filtered Data)

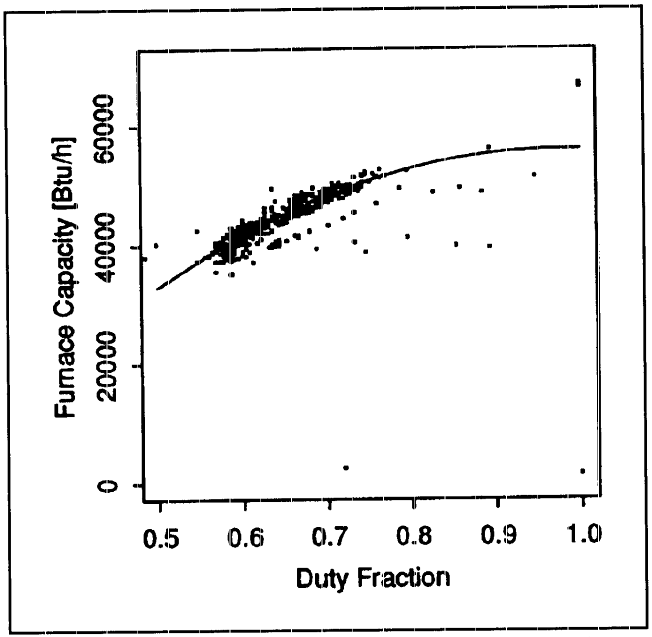

Figure 4. Furnace Capacity Map (Filtered Data)

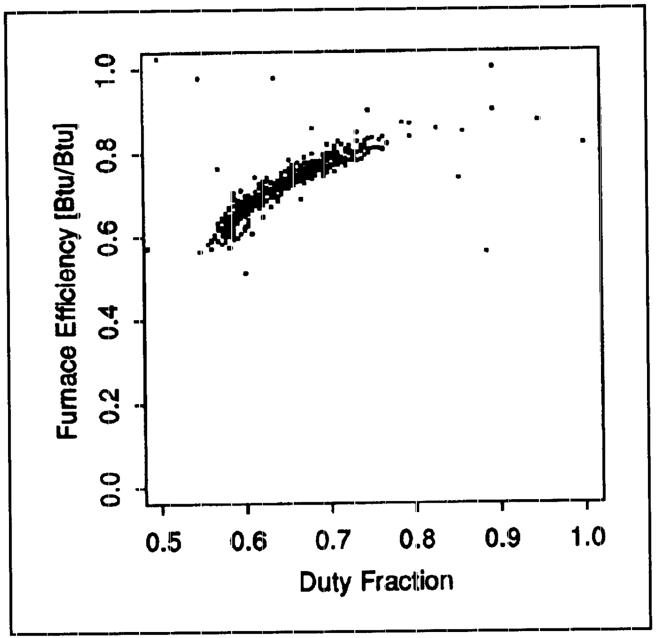

Figure 5. Furnace Efficiency (Filtered Data)

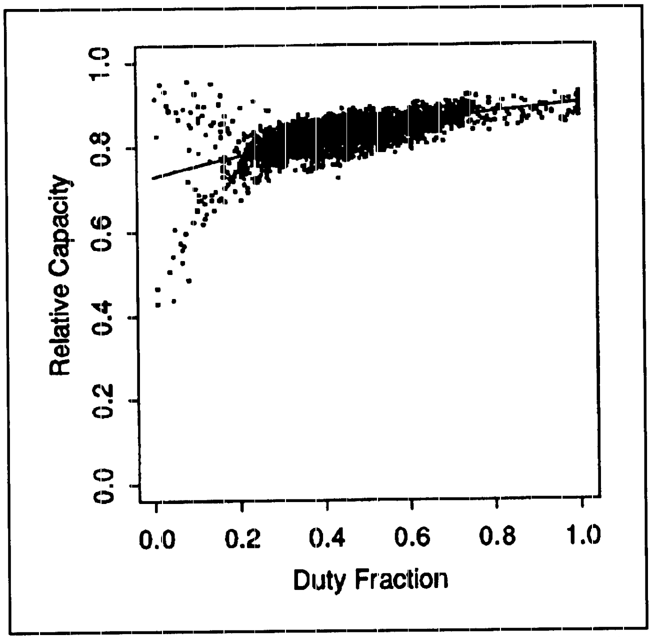

Figure 6. Map of Air-Conditioner Field Capacity Relative to Manufacturer's Steady-State Data

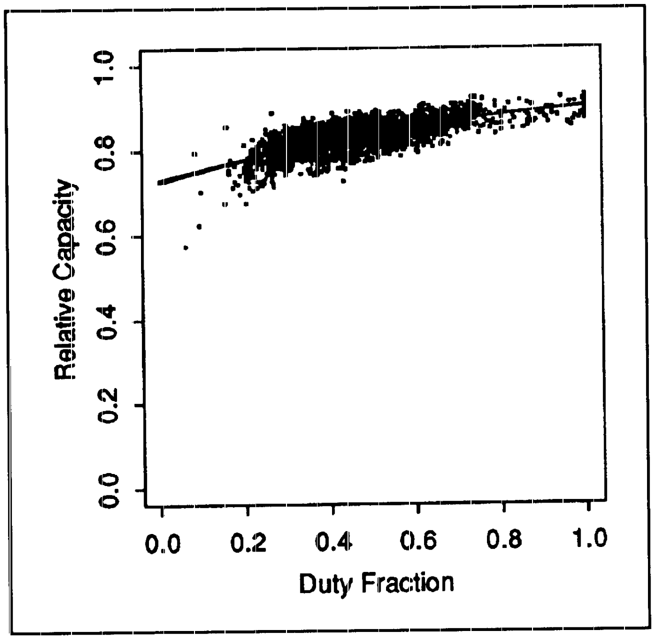

Figure 7. Map of Relative Capacity (Filtered Data)

The air-conditioner performance is shown in Figure 6 as a plot of C/C_{ss} or C_{pl} as a function of duty fraction [see Equation (1)]. The reduction in performance with decreasing loads is not as strong as with the furnace data but is visible and illustrated with a line from a quadratic fit to the data. Some pure startup and pure shutdown points are seen in a double tail of data points at low duty fraction. Figure 7 shows the result of processing the data with the digital filters. Here the isolated partial events in the two tails of Figure 6 have been added to the corresponding logger periods that have the remainder of the events. A fit to the aggregated data is plotted in Figure 7 and shows only very slightly lower capacities at low duty fraction when compared to a fit to the unaggregated data (also shown in Figure 7). A component of the noise in the plot comes from severed cycling events that are not reassembled by the logic filter.

In one of the houses the cycling rate was low enough that nearly all of the air-conditioning events could be isolated.

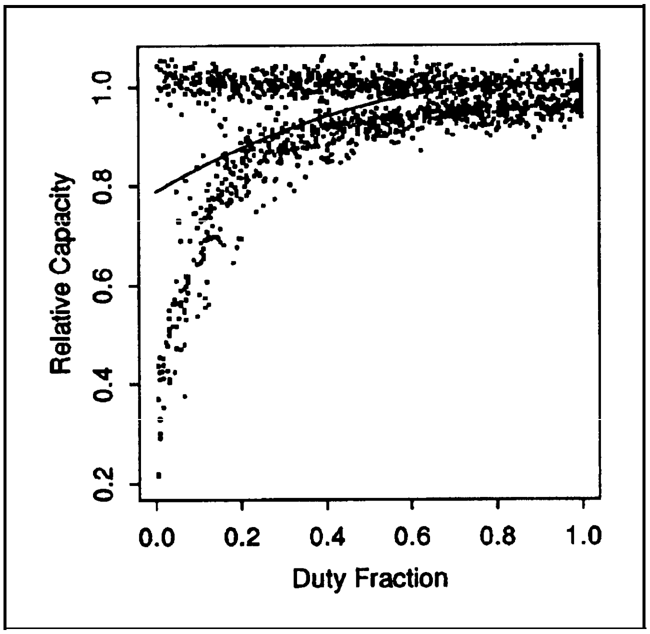

Figure 8. Map of Relative Capacity (High Resolution Data)

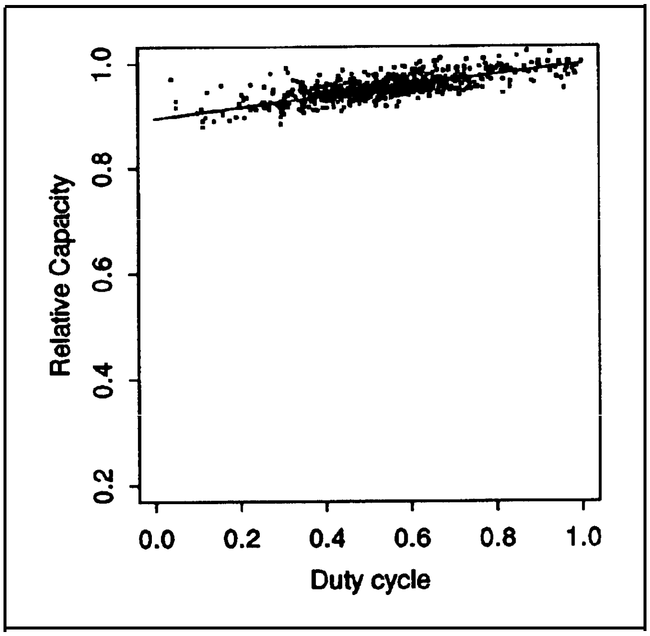

Figure 9. Map of Relative Capacity by Duty Cycle (Filtered Data)

This is seen clearly in Figure 8 where nearly all of the events are severed by logger interval boundaries. The high resolution of this data allowed the duty cycle to be calculated for each event. The results is a much more correlated response of capacity to part-load operation in Figure 9. The stronger correlation results because the duty cycle plot has a point for each cycle event and also distinguishes events with similar run times by the length of the prior off period. The duty cycle data appears to remove an apparent duty-fraction bias of lower performance at lower loading. This can be seen by comparing the fits in Figure 8 and Figure 9.

Because of the importance of duty cycle data in the mapping process, the field loggers were adapted for a higher sampling rate and also equipped with an additional digital channel in Spring 1994. This channel counts the times the fan turns off during a logger cycle. The additional cycling information and sampling resolution gives the event isolation needed for duty cycle analysis.

Conclusions

The Fort Sam Houston baseline data has demonstrated how performance mapping techniques can be used to quantify part-load performance in conventional air conditioners and furnaces. These maps serve as simple empirical models and can be used to predict performance of the units under a wide range of loading and operating conditions. Mapping air-conditioner performance relative to correlations of manufacturers' steady-state data has proven to be a useful approach in establishing the psychometric dependence in the maps.

Data sampling is a critical issue in interpreting the field data. Time-stamp characterization of HVAC events clearly has advantages over interpreting cycling events in fixed-interval logger periods. However, logic filters have shown to be successful in reassembling HVAC events and removing sampling anomalies from the performance maps.

Acknowledgments

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