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Monitored In-Situ Performance of Residential Air-Conditioning Systems

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ABSTRACT

Residential air-conditioning systems are considered essential in many parts of the United States. These products should be selected based on a comparison of the estimated heat gain to the manufacturer's performance specifications. The selected air conditioners should then be installed to the manufacturer's specifications. The reality departs significantly from this scenario. In the end, air conditioners are selected and installed under field conditions that degrade performance.This study examines three measured factors that affect performance: cooling load, capacity, and attic temperatures. These results were obtained from four intensively monitored, new single-family homes in Phoenix, Arizona.

This study found that the most widely accepted sensible heat gain calculation, applied without "safety" factors, overestimated the sensible heat gain for these homes by approximately 50%.

Two of the five air conditioners had sensible capacities significantly below specifications. Both air conditioners with deficient capacity had low airflow and one was seriously undercharged.

Attic temperatures are critical in forced-air distribution efficiency when the ducts are in the attics. On these homes, attic temperatures at peak ranged from 28°F (16°C) to 4°F (2°C) above outside temperatures.

INTRODUCTION

The Phoenix metropolitan area is one of the fastest growing markets for new residential units in the nation. It is also an area of low humidity and very low latent cooling loads typical of other Sun Belt cities. This study was a portion of a 22-home research project conducted for a local utility. The utility was interested in energy savings and peak demand reductions achievable from a heating, ventilating, and air-conditioning (HVAC) efficiency program.

Four homes were intensively monitored (five monitored air conditioners). The monitored temperatures on these systems generally included: return plenum, supply plenum, duct location (usually attic), return grille, supply grille, outdoor, second duct location, indoor coil, and suction line. The data acquisition system also recorded air-conditioner status and condensate flow. These data were supplemented with temperature and humidity information from the local weather station and extensive one-time diagnostic tests.

SAMPLE

The four homes were selected to represent typical single-family housing as found in the Phoenix new construction market. The houses were occupied and less than one year old. The typical house in the study was a slab-on-grade home with three bedrooms, about 2100 ft^2 (195 m^2) of living space, a volume of about 19,500 ft^3 (552 m^2), double-glazed windows, and 30 h ft^2 (F/Btu (5.3 m^2 K/W) attic insulation with a tile roof. All of the houses had an air handler located in the attic. The two-system house had two stories, and the second air handler was in the garage. No modifications were made to the systems in three of the homes except for the installation of sensors. The fourth home was modified to provide controllable duct leakage as described in a later section of this paper.

The houses were tight, with an average blower door measured air leakage of 1959 cfm (925 L/s) at 0.20 in. H_2O (50 Pa) pressure. Blower door measurements and a national laboratory's infiltration model (Sherman 1987) were used to estimate the natural infiltration rate for these homes (calculated using wind speeds published in ASHRAE [1993.]) and bin weather data published in Rutkowski [1986], based on an indoor temperature of 70°F [21°C] in winter and 75°F [21°C]

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TABLE 1
Sensor Locations

Input	Location	Parameter
Temperature #1 (Analog Grid)	Return plenum	Temperature of air entering air handler
Temperature #2 (Analog Grid)	Supply plenum	Temperature of air exiting coil
Temperature #3 (Analog)	Attic (midway between the ceiling and the roof peak)	Duct/AH location temperature
Temperature #4 (Analog)	Return grille	Temperature of air entering the return duct
Temperature #5 (Analog)	Supply register	Temperature of air leaving a main supply duct
Temperature #6 (Analog)	Shaded outdoor	Outdoor ambient temperature
Temperature #7 (Analog)	Secondary duct location	Temperature of second duct location
Temperature #8 (Analog)	Indoors	Temperature by thermostat
Temperature #9 (Analog)	DAS reference	Temperature at the terminal strip
Temperature #10 (Analog)	Evaporator coil	Saturation temperature of coil
Temperature #11 (Analog)	Suction line at AH	Temperature of suction line
AC Current (Pulse)	Power wire at compressor	Air-conditioner status
Tipping Bucket Gauge (Pulse)	Condensate drain	Condensate flow

in summer). The modeled summer season natural ACH of the homes in the project averaged 0.29.

MONITORING

These homes were monitored by a data acquisition system (DAS). The DAS has the flexibility to perform many data acquisition functions and is capable of being downloaded or reprogrammed via modem. The temperature probes were bare wire, 36 gauge, type T thermocouples. The electrical current was sensed with a 50 amp split core current transducer. The reference temperature for the thermocouples was provided by a thermistor. Condensate flow from the indoor coil was measured with the use of a tipping bucket gauge attached to the termination of the condensate drain. The data points are summarized in Table 1. Sensor locations were determined in advance based on past instrumentation experience and the research questions being addressed in this study.

FINDINGS—MEASURED COOLING LOAD (HEAT GAIN)

The first area of interest from the monitored data is the cooling load of the homes. The monitored data include supply plenum temperature and return plenum temperature averaged over the on-cycle of the air conditioner. The airflow across the heat exchanger was measured at the time the monitoring equipment was installed and at the time of removal. From these data points, the delivered sensible capacity of the air conditioner was calculated for each cycle. The delivered capacity over each monitored hour was calculated.

When the air conditioner is able to maintain interior temperature, the delivered sensible capacity (DSC) equals the sensible load of the home.

The heat gain was estimated using the most widely accepted method (Rutkowski 1986). The heat gain at design (estimated design load, or EDL) was calculated using conservative inputs (the low infiltration rates of the homes were used, existing shading and other window treatments were accounted for, and no "safety" factors were applied to the inputs or results).

The estimated design load is compared to the measured hourly loads (delivered sensible capacity) for each home in the following section. The homes are identified by their system numbers.

System 23

System 23 was in a single-system home where the occupants kept a constant thermostat setting. Figure 1 displays the sensible load seen by this air conditioner.

The 2.5% design dry-bulb temperature for Phoenix is 107°F (42°C) (ASHRAE 1993). This temperature is designated by the vertical line in Figure 1. In a normal summer, the

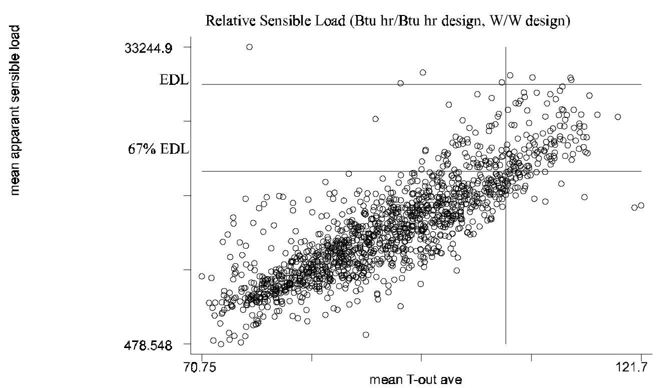


Figure 1 *Sensible load, System 23.*

temperature will equal or exceed that temperature 73 hours. If the estimated design load were perfectly accurate, the house sensible cooling load would equal or exceed EDL for 73 hours in a normal summer. As shown in Figure 1, the load exceeded EDL for only 8 hours. A revised load estimate of 67% EDL more accurately predicts the actual sensible load for this house in this summer (67% was used based on data in this study, as well as data from a similar study in Las Vegas [Proctor et al. 1997]). The sensible load exceeded 67% EDL for 186 hours during the monitored period, which was an abnormally hot summer.

Systems 5 and 6

Systems 5 and 6 were in a two-system house. The occupants adjusted their thermostat up on the upstairs unit and down on the downstairs unit in the morning. In the evening, the thermostats were adjusted higher downstairs and lower upstairs. Figure 2 displays the thermostat setting behavior in this home.

The sensible load seen by these two air conditioners is combined in this analysis. Figure 3 displays the sensible load against the outdoor temperature.There were 68 hours that the

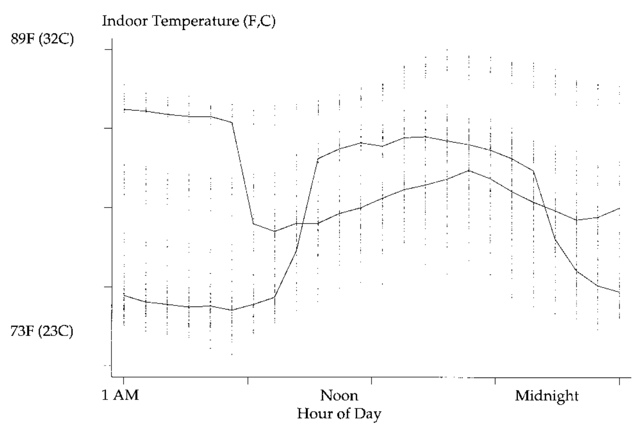


Figure 2 *Thermostat settings, Systems 5 and 6.*

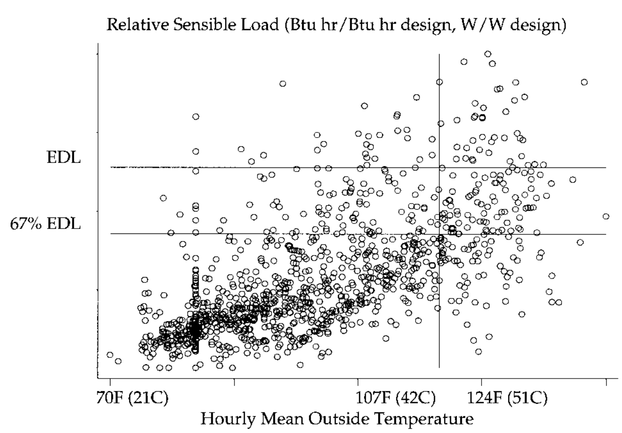


Figure 3 *Delivered sensible capacity, Systems 5 and 6.*

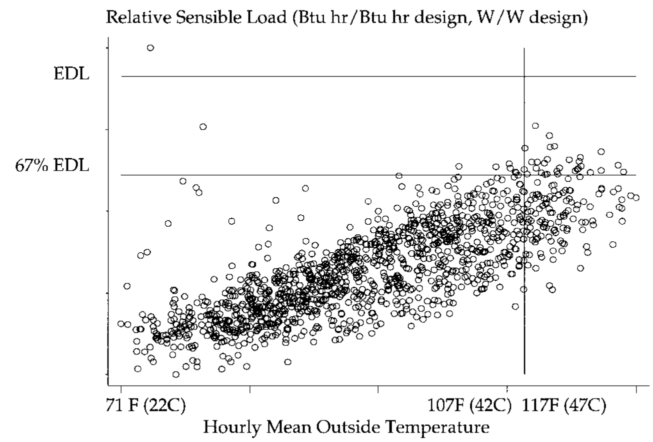


Figure 4 *Sensible load, System 25.*

delivered sensible capacity exceeded EDL for this house. This was attributed to the thermostat adjustments.

System 25

System 25 was in a single-system home. Occupants kept a nearly constant thermostat setting. Figure 4 displays the sensible load seen by the air conditioner against the outdoor temperature. There was one hour that the sensible load exceeded EDL and 38 hours that the sensible load exceeded 67% EDL.

System 24

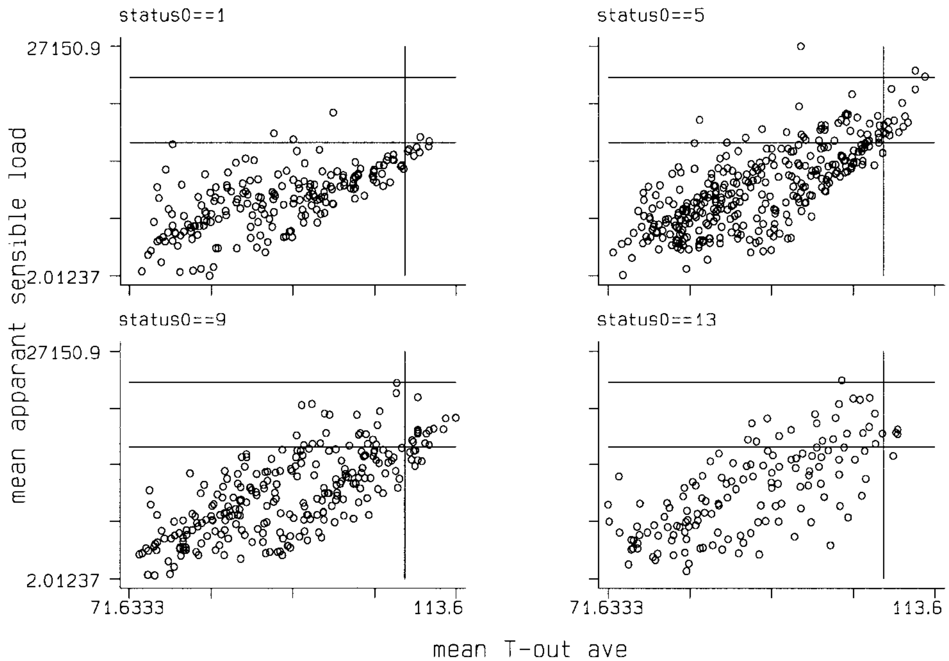
System 24 was used for a special test. It was modified to have duct leaks that were controlled by the data acquisition system. This flip-flop experiment is described in detail in Proctor et al. (1997). This system had four modes of operation:

1. *Baseline*—Return leakage fraction 11.2% and supply leakage fraction 15.8%.
2. *Supply leak only*—Return leakage fraction 3.3% and supply leakage fraction 15.8%.
3. *Return leak only*—Return leakage fraction 11.2% and supply leakage fraction 2.5%.
4. *Ducts sealed*—Return leakage fraction 3.3% and supply leakage fraction 2.5%.

Since the cooling load includes the distribution losses, there were four cooling loads measured (one for each mode of operation). These loads are displayed in Figures 5 and 6. Occupants kept a constant thermostat setting in the period of analysis.

The critical nature of duct leakage is clearly shown in the shift in cooling load between different amounts of duct leakage. It is also clear that even under the worst leakage mode, the sensible cooling load was significantly less than the estimated design load even well above design temperatures.

Table 2 shows the frequency of sensible loads equaling or exceeding EDL and 67% EDL.



Status0==1 is Ducts Sealed
Status0==5 is Supply Leaks Only
Status0==9 is Return Leaks Only
Status0==13 is Baseline

Figure 5 *Sensible load, System 24, all modes.*

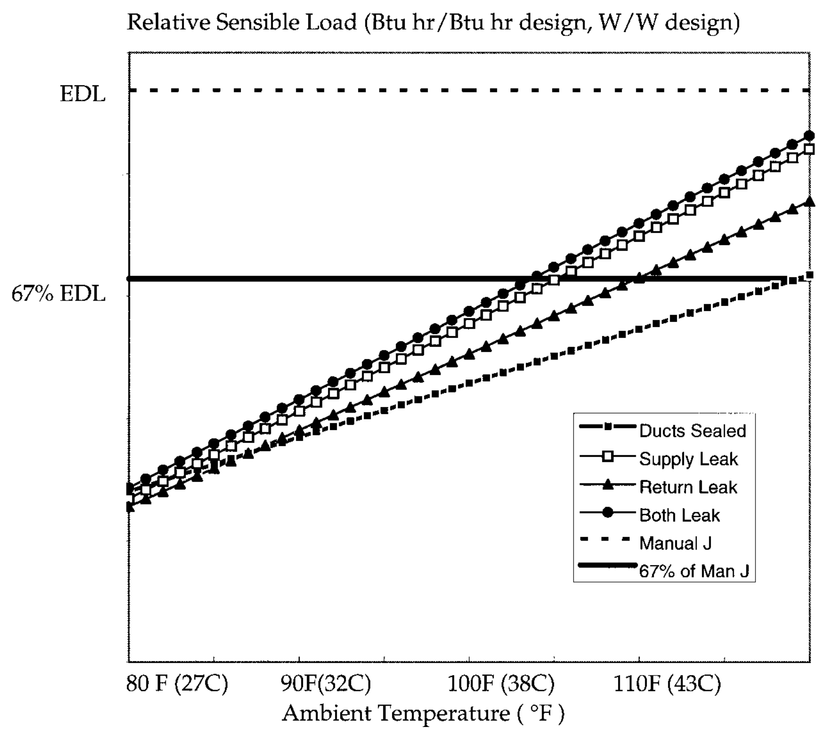


Figure 6 *Sensible load trend, System 24, all modes.*

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TABLE 2
System 24 Hours Equaling or Exceeding Estimated Design Load

Mode	EDL	67% EDL
Baseline	1 Hour	25 Hours
Supply Leak Only	3 Hours	35 Hours
Return Leak Only	0 Hours	51 Hours
Ducts Sealed	0 Hours	5 Hours

FINDINGS—AIR CONDITIONER SENSIBLE CAPACITY

The second area of interest is the in-situ sensible capacity of the air conditioners in these homes. The monitored data include end of on-cycle supply plenum temperatures and return plenum temperatures. From the airflow and temperature drop, the “near steady state” sensible capacity of the air conditioner was calculated for each cycle. Table 3 lists the measured sensible capacity at design conditions.

The actual capacity is sometimes substantially less than that shown in the manufacturer’s tables due to installation problems (Blasnik et al. 1995a, 1995b; Neal and Conlin 1988; Proctor and Pernick 1992). Table 3 compares the measured sensible capacity, modeled sensible capacity from manufacturer’s tables, and estimated design load all at 2.5% design conditions.

Systems 23 and 24 perform substantially below their designed capacity but still above the estimated design load (and, therefore, much above the actual load). The performance of these two systems is poor primarily due to installation errors. System 23 has 82% correct airflow across the coil. System 24 has 69% correct airflow across the coil and 64% of correct charge. The other three systems (5, 6, and 25) have near correct airflow and charge.

FINDINGS—ATTIC TEMPERATURES

The performance of air-conditioning systems is strongly affected by the distribution efficiency of the forced-air delivery system, as previously made evident in Figures 5 and 6. For attic ducts, particularly with return leaks, the attic temperature is a critical factor. As the attic temperature rises, the effect of return leaks drawing the attic air into the duct system increases. Figures 7 through 9 show the average monitored hourly outdoor and attic temperatures for all days with maximum temperatures exceeding the Phoenix design temperature of 107°F (42°C).

These homes had tile roofs that substantially reduce the attic temperatures. Each home also had attic ventilation in excess of code requirements. It is noteworthy that for much of the day, the attic temperatures are below outside temperature. The air conditioner is cooling the attic, either directly through supply duct leaks and conduction or indirectly through ceiling conduction.

Attic temperatures displayed in Figures 7-9 were taken halfway between the peak of the roof and the top of the ceiling insulation near the center of the home.

TABLE 3
Measured Sensible Capacity at Design

	Measured Sensible Capacity Btu/h (W)	Modeled Total Net Capacity from Mfr.'s Tables Btu/h (W)	Estimated Sensible Design Load Btu/h (W)
System 5	19673 (5766)	22762 (6671)	28610 (8385) Sensible Load for Systems 5 and 6 Combined
Std. Deviation	1631 (478)		
Cycles (n)	210		
System 6	28570 (8373)	29179 (8552)	
Std. Deviation	1259 (369)		
Cycles (n)	199		
System 23	30185 (8847)	38816 (11376)	28221 (8271)
Std. Deviation	640 (187)		
Cycles (n)	226		
System 24	27380 (8025)	38540 (11296)	23461 (6876)
Std. Deviation	2992 (876)		
Cycles (n)	182		
System 25	18053 (5291)	22720 (6659)	16582 (4860)
Std. Deviation	578 (169)		
Cycles (n)	362		

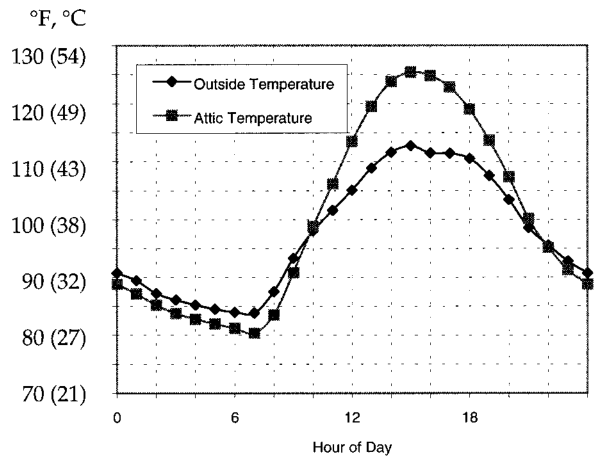

Figure 7 *Attic and outdoor temperatures, System 6.*

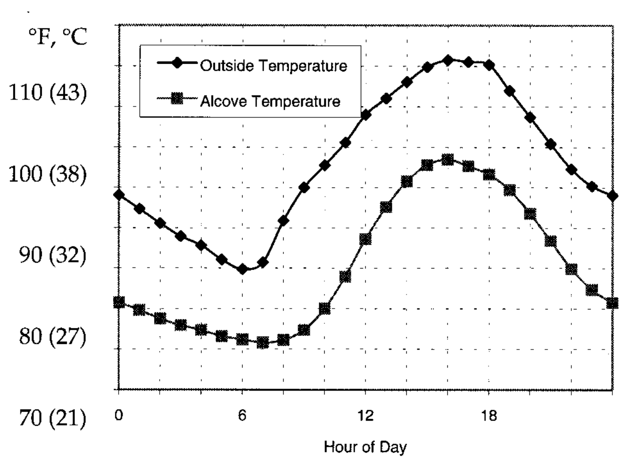

Figure 8 *Attic alcove and outdoor temperatures, System 23.*

System 6

System 6 was the attic system in the two-system home. The thermostat was set at 85°F (29°C) during the day, resulting in less run time even on peak days. This system had the second highest attic temperatures of the sample. At its peak, the attic temperature was 13°F (7°C) above the outside temperature.

System 23

The indoor unit for System 23 was in an alcove in the attic surrounded by batt insulation. The temperature in the alcove is not representative of the general attic temperature, but it clearly shows the effect of supply leakage and conduction around the unit. The alcove temperatures are always below the outside temperature, as shown in Figure 8.

The majority of the ductwork for System 23 was outside the alcove. The general attic temperature was monitored by an additional probe positioned in the center of the attic midway

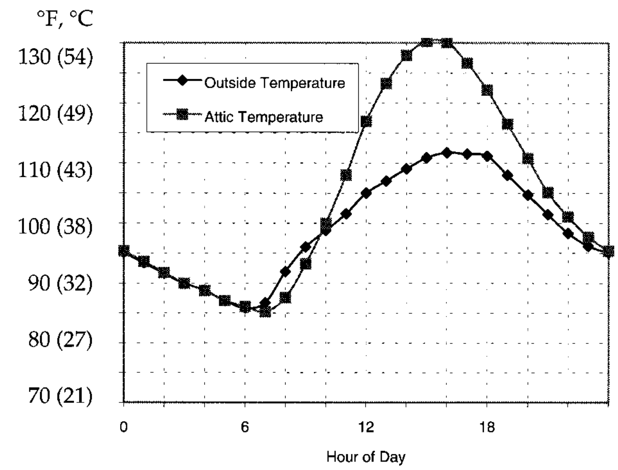

Figure 9 *Attic and outdoor temperatures, System 23.*

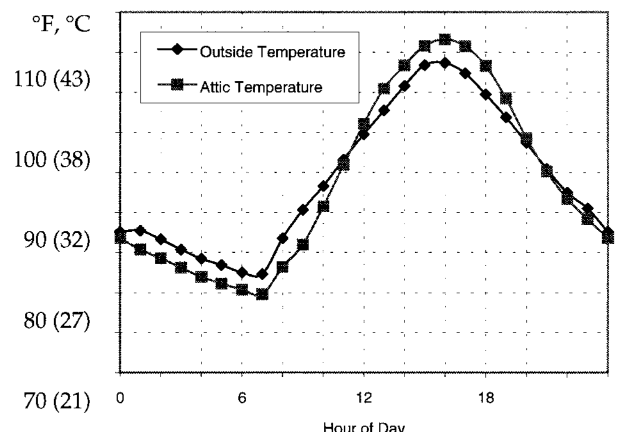

Figure 10 *Attic and outdoor temperatures, System 24.*

between the ridge and the top of the ceiling insulation. Since the cooling effect of the conduction and supply leaks in the area of the cabinet were confined to the alcove, the general attic temperature was the highest of the sample. The peak difference between attic and outside temperature was 28°F (16°C). The general attic temperature is shown in Figure 9.

System 24

System 24 had the smallest attic temperature elevation above outside at peak. The results from the primary sensor were checked against the second attic temperature sensor. The two temperatures were found to be consistent with each other. The maximum attic temperature elevation above outside was 4°F (2°C). The temperatures are displayed in Figure 10.

System 25

System 25 was a common system design. The maximum attic temperature elevation above outside was 11°F (6°C). The temperatures are displayed in Figure 11.

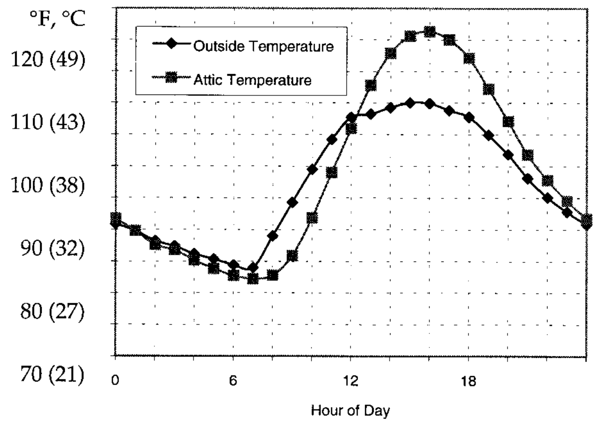

Figure 11 *Attic and outdoor temperatures, System 25*

CONCLUSIONS

The most widely accepted sensible heat gain calculation, applied without "safety" factors, overestimated the sensible heat gain for these homes by approximately 50%. This result is likely to apply to hot, dry climates. Given that the sensible heat gain calculation is identical regardless of climate, it is not unlikely that it would also apply to the sensible portion of the cooling load in hot, moist climates.

The measured air-conditioner sensible capacity was significantly less than manufacturers' tables would indicate for two of the five units in this sample. Common installation errors (particularly incorrect refrigerant charge) are the most likely cause of these deficiencies.

Attic temperatures at design conditions were quite variable. They are dependent not only on solar gains and ventilation but also on conduction through the ceiling, conduction across the duct and air- handler cabinet, the location and size of duct leaks, and the construction of the space containing the air handler. Attic temperatures are a major variable in the distribution efficiency when ducts run through the attic.

RECOMMENDATIONS

Additional homes in other climates should be monitored to determine the true heating load and cooling load. The existing and future load estimation methodologies must be field verified to avoid oversizing heating and cooling equipment. With the addition of accurate humidity sensors in the airflow path, the method used in this investigation is adequate for these purposes.

The air conditioner/heat pump market needs to be transformed. Improved air conditioner and heat pump installation methodologies need to be applied to ensure proper charge and airflow. These installation methodologies need to include immediate feedback to the installer that the equipment is operating properly.

ACKNOWLEDGMENTS

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