Energy Savings and HVAC Capacity Implications of a Low-Emissivity Interior Surface for Roof Sheathing

Robert Hageman, KoolPly
Mark P. Modera, Lawrence Berkeley National Laboratory

The idea of reducing heat flow across the ceiling of a house with a radiant barrier has been studied for many years. However, one issue that has not been adequately addressed is the impact of a radiant barrier on the performance of a typical residential duct system located in the attic. This paper describes the results of a field investigation of a radiant barrier placed on the inside of the roof sheathing. The study is based upon measurements of attic and ceiling temperatures, duct-system temperatures and flows, and A/C electricity use of a new house located in Austin, Texas, before and after installing a radiant barrier on the roof sheathing. The house tested had R-38 °F ft^{2}h/Btu attic insulation, foil-faced R-6 °F ft^{2}h/Btu insulation on the ducts (all within the attic, along with the air handler), and 1 ft^2 of attic venting area per 150 ft^2 of ceiling area. Based upon detailed comparison of the weather conditions pre- and post-retrofit, the air-conditioner energy consumption was found to decrease by 16% after the retrofit. Further analysis shows that 80% of this savings is attributable to improved performance of the duct system. In addition, at 5:00 PM the load seen by the HVAC equipment is reduced by 4500 Btu/h (or 15% of the nominal capacity of the air conditioning equipment).

INTRODUCTION

The idea of reducing heat flow across the ceiling of a house by reducing the radiative heat exchange between the top side of that ceiling and the roof deck has been around for many years (Fairey 1985, Levins and Karnitz 1986, Levins and Karnitz 1987, Levins et al. 1989). The technologies used to effect this reduction in radiative exchange are commonly known as radiant barriers, and have generally consisted of aluminized plastic sheets located directly on top of the ceiling, or attached in some manner to the roof rafters. Numerous studies of the energy-savings potential of radiant barriers in residential attics have been performed over the past ten years (Levins and Karnitz 1987a, Levins and Karnitz 1988, Fairey 1990), and the American Society for Testing and Materials (ASTM) has a standard for evaluating the performance of these systems (ASTM C1158–90). The general conclusion of the published studies has been that the energy savings potential is greatest in houses with relatively little ceiling insulation in sunny cooling-dominated climates. There is however at least one energy issue that has not been adequately addressed by either field study or simulation-based analyses, namely, the impact of a radiant barrier at the roof-sheathing on the performance of a typical residential duct system located in the attic.

This paper describes the results of a field test designed to investigate the impacts of an attic radiant barrier placed on the underside of the roof sheathing for a well-insulated attic containing ductwork. The basic design of the study was to quantify the impacts of such a radiant barrier by measuring various temperatures and the A/C electricity use of a house before and after installing a radiant barrier on the bottom side of the roof sheathing.

METHODOLOGY

The basic experimental design was to monitor the performance of an unoccupied energy-efficient house over several days of summer conditions, to then retrofit that house with a radiant barrier on the underside of the roof sheathing, and then to monitor the performance of the house for several days after the retrofit, assuring that there was at least one day of post-retrofit data under weather conditions that were comparable to those on a day from the pre-retrofit period.

The house chosen for testing was a house built in 1995 in Austin, Texas to ''Good Cents'' specifications (LCRA 1995). The pertinent characteristics of the house are presented in Table 1.

Several points worth noting relative to Table 1 are: 1) that the capacity of the air conditioner is consistent with the City of Austin requirement of 1 ton of air conditioning per 600 ft^2 of house floor area, 2) that the roof pitch results in an attic height of approximately 10 ft (3 m) at the peak, and 3) that the attic vents consisted of two gable end vents located just below the peak (6 ft^2 (0.6 m^2) each), three roof ventilators located near the peak (0.6 ft^2 (0.05 m^2) each), and nine soffit vents (0.9 ft^2 (0.08 m^2) each).

Table 1. Characteristics of Test House

Characteristic	Value
Floor Area [ft^2(m^2)]	1530 (142)
Foundation Type	Slab-on-Grade
Ceiling Construction	Flat Ceiling, 9 ft (2.7 m) high
Duct Location	Attic
Air Handler Location	Attic
Envelope Leakage [ACH@50Pa (cm^2 leakage area /m^2 floor area)]	5.2 (2.6)
Ceiling Insulation R-Value [°F ft^{2}h/Btu (°C m^2/W)]	38 (6.7) blown fiberglass
Duct Insulation R-value [°F ft^{2}h/Btu (°C m^2/W)]	6 (1) plastic/fiberglass flexduct with aluminized outer vapor barrier
Roof	6 in 12 pitch, brown composition shingles
Attic Venting Area [ft^2(m^2)]	22 (2)
Effective Attic Venting Area [ft^2(m^2)]	10 (1)
Nominal A/C Capacity [tons (kW)]	2.5 (8.8 kW)
System Air Flow [cfm (m^3/h)]	1570 (2670)
Roof Sheathing Surface Area [ft^2(m^2)]	2560 (238)

Diagnostic Measurements

The diagnostic tests performed on the house included measurements of the flows into and out of each air-distribution-system register, a blower-door measurement of the envelope leakage, and a smoke test for duct leakage. The measurements of register flows were performed on two separate days by a field engineer for the Lower Colorado River Authority Good Cents Program using a Shortridge Instruments Flowhood (Shortridge AIR-DATA, Multimeter ADM-850 Electronic Micro Man-O-Meter). The two sets of measurements agreed to within 2% on the total flow. These measurements indicate that the air handler was moving 630 cfm/ton, considerably more than the ‘‘typical’’ 400 cfm/ton. This elevated air flow is attributed to the fact that the duct system was oversized so as to reduce static pressure and assure proper air distribution. Oversizing the ducts implies that the duct system might have more surface area than is typical, however this was not the case (22% of conditioned floor area versus a typical value of 24% (Luciani 1992)), probably due to the relatively central air handler location, and the geometry of the house.

The blower door measurements indicated that the envelope was relatively airtight, its leakage being somewhat less than the average value of 6.8 ACH@50Pa (3.4 cm^2 per m^2 floor area) measured for overall shell leakage (i.e., including duct leakage to outside) in twenty new California houses (CEC 1995).

Monitoring Data

The monitoring used for the analysis performed included 20 on-site temperatures measured with thermocouples (Type J) connected to a data acquisition system, A/C power consumption measured with a watt-hour submeter installed by the local utility (Pedernales Electric Cooperative), outdoor temperature and windspeed data obtained from the National Weather Service at Austin airport, and solar flux measured by the City of Austin Electric Utility Department. The on-site temperatures were plotted continuously on a chart recorder and recorded digitally every six minutes for a seven-day period (Yokogawa Model HR 1300 22). The thermocouple/data-acquisition-system combination had been calibrated by the factory two weeks prior to the measurements, the specified accuracy being 0.9 °F (0.5 °C), with a resolution of 0.2 °F (0.1 °C). The A/C consumption data was recorded every 15 minutes, and included whole-house as well as A/C condenser (compressor plus outdoor fan) data. All of the weather data are hourly values, as recorded by the National Weather Service.

RESULTS

The house was run with a constant thermostat setting of 75 °F (24 °C) for a seven-day period starting July 15 and ending July 23, with the addition of a radiant barrier under the roof sheathing on July 20. Two days, July 19 and July 22, that had comparable weather conditions are used to compare the performance of the house, the ceiling and the duct system before and after stapling the radiant barrier on to the bottom side of the roof sheathing.

The impacts of the radiant-barrier sheathing retrofit is examined several ways. First, the overall impact of the radiant barrier on the electricity consumption of the air conditioner is examined, with and without weather corrections. Then, the impacts of the radiant barrier on energy losses from the supply ducts and return ducts as well as ceiling heat flux are separately quantified so as to calculate their relative contributions to the observed overall reduction in electricity consumption.

Weather Comparison

The weather conditions measured on July 19 and July 22 are compared in Figures 1–4. Figure 1 compares the hourly outdoor temperatures measured by the National Weather Service at the Austin airport; Figure 2 compares the hourly solar flux measured by the City of Austin Electric Utility Department; and Figure 3 compares the windspeeds measured by the National Weather Service at the Austin airport. Figure 4 compares outdoor-air enthalpies obtained from outdoor temperature and relative humidity data from the National Weather Service at the Austin airport, which are needed to calculate the cooling load impacts of any changes in air infiltration between the two days. The house tested is located approximately 15 miles from the Austin airport, and generally has weather conditions similar to those at the airport.

Figures 1 and 2 indicate that the outdoor temperature and solar flux were similar for the pre- and post-retrofit days being compared. The average outdoor temperature was 87 °F (30.5 °C) on the day after the retrofit, as compared to 86.2 °F (30.1 °C) for the pre-retrofit day. This 0.8 °F (0.4 °C) corresponds to a 7% higher indoor-outdoor temperature differential on the post-retrofit day. The average solar fluxes on the two days were within 1% of each other (the flux during the post-retrofit period was 0.4% higher). On the other hand, Figure 3 makes it clear that the windspeed was higher during the post retrofit period, which can have an impact on the analysis of the retrofit performance. The differences in outdoor air enthalpy in Figure 4 are plotted only because of their influence on air infiltration loads.

Overall Impact of Radiant-Barrier Sheathing on A/C Electricity Consumption

The overall impact of the radiant-barrier sheathing retrofit on electricity demand/consumption and HVAC system operation is plotted in Figures 5 and 6. Figure 5 is a plot of three-point rolling averages of the 15-minute energy consumption data that have not been modified for the observed differences in windspeed between July 19 and July 22. Figure 6 is a similar plot for the fractional on-time of the air conditioner on those two days.

Figure 5 shows clear reductions in A/C electricity draw associated with the addition of the radiant barrier. The electricity consumption is reduced by 14% between 11:15 AM and 10:15 PM. Figures 5 and 6 also indicate that air conditioner is running continuously for some fraction of the day both before and after the addition of the radiant barrier, however it is on continuously for more than five hours pre-retrofit (3:30 PM to 8:45 PM), and less than two hours post-retrofit (6 PM to 7:30 PM). It should be noted that the electricity consumption data was taken on 15-minute intervals, and was temporally smoothed (rolling 3-point average) to make Figure 5 easier to read, however this makes it more difficult to pinpoint the time at which the air-conditioner actually turned on and off. Thus, analysis of the continuous chart recorder plots of the air temperature directly after the A/C coil indicate that on July 19th, the air-conditioner turned on at 2:50 PM, and turned off at 9:00 PM, and that the corresponding times for July 22nd were 5:30 PM and 8:00 PM. Thus, the electricity demand of the air conditioner during the utility's peak (either system-wide or local-area) is reduced by the radiant sheathing as long as the utility peak occurs at any time other than between 5:30 PM and 8:00 PM. It should be noted that this ‘‘topping-out’’ of the air conditioner after the retrofit might not have occurred if the air conditioner had been sized larger, or if the duct system was better insulated or more air-tight.

As noted above, the windspeed during the post retrofit period can impact our analysis of the performance of the radiant barrier. The implications of this higher windspeed include:

Figure 1. *Hourly outdoor temperature measured by National Weather Service at the Austin airport on July 19, 1995 (pre-retrofit) and July 22, 1995 (post-retrofit)*

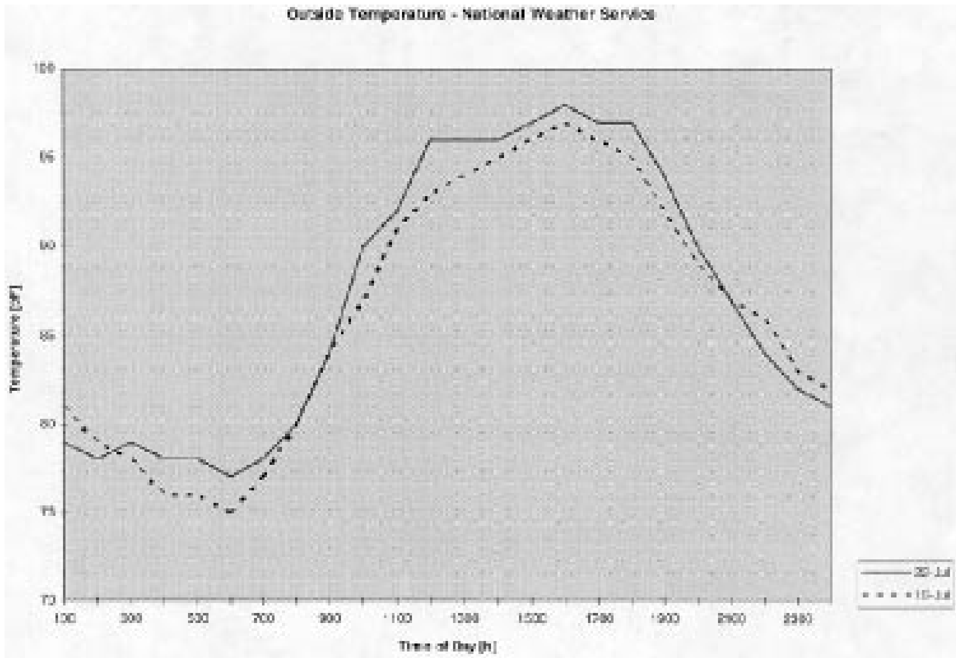


Figure 2. *Hourly solar flux measured by City of Austin Electric Utility Department on July 19, 1995 (pre-retrofit) and July 22, 1995 (post-retrofit)*

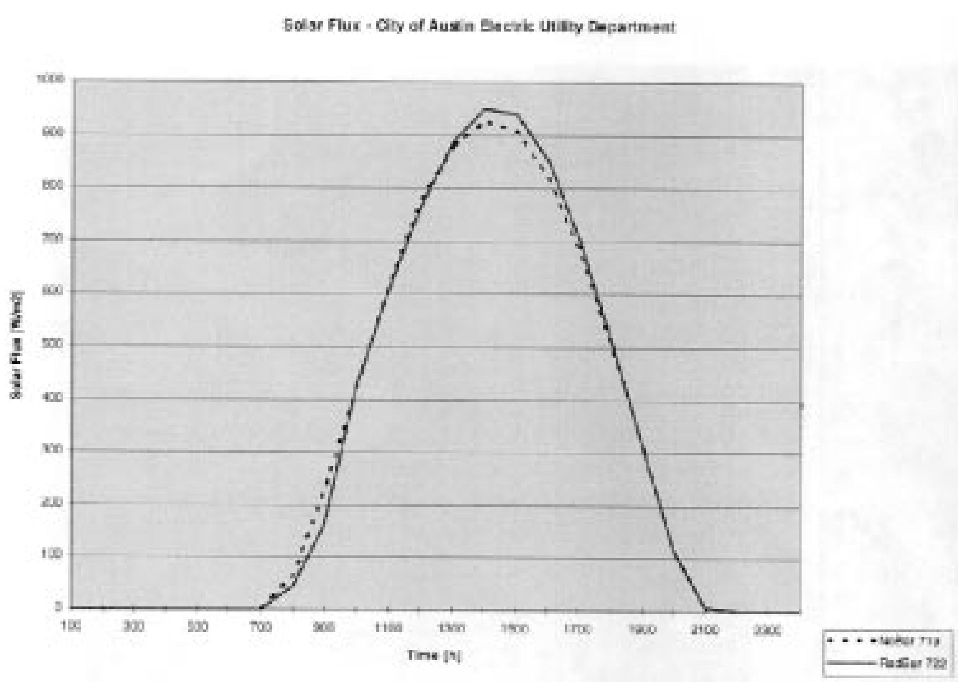


Figure 3. *Hourly windspeed measured by National Weather Service at the Austin airport on July 19, 1995 (pre-retrofit) and July 22, 1995 (post-retrofit)*

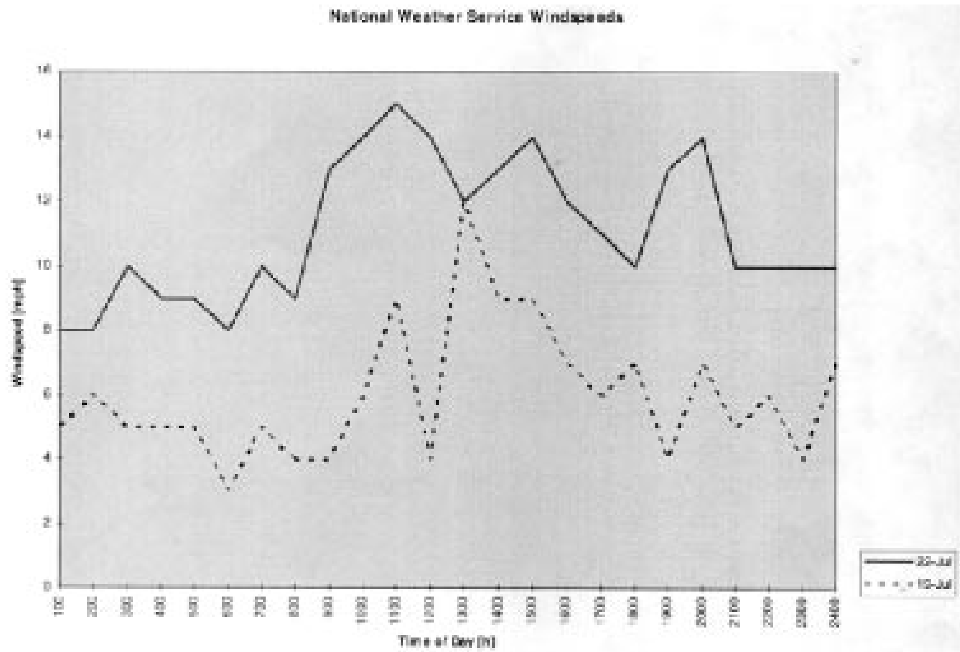


Figure 4. *Hourly outdoor enthalpies airport on July 19, 1995 (pre-retrofit) and July 22, 1995 (post-retrofit) calculated from National Weather Service data*

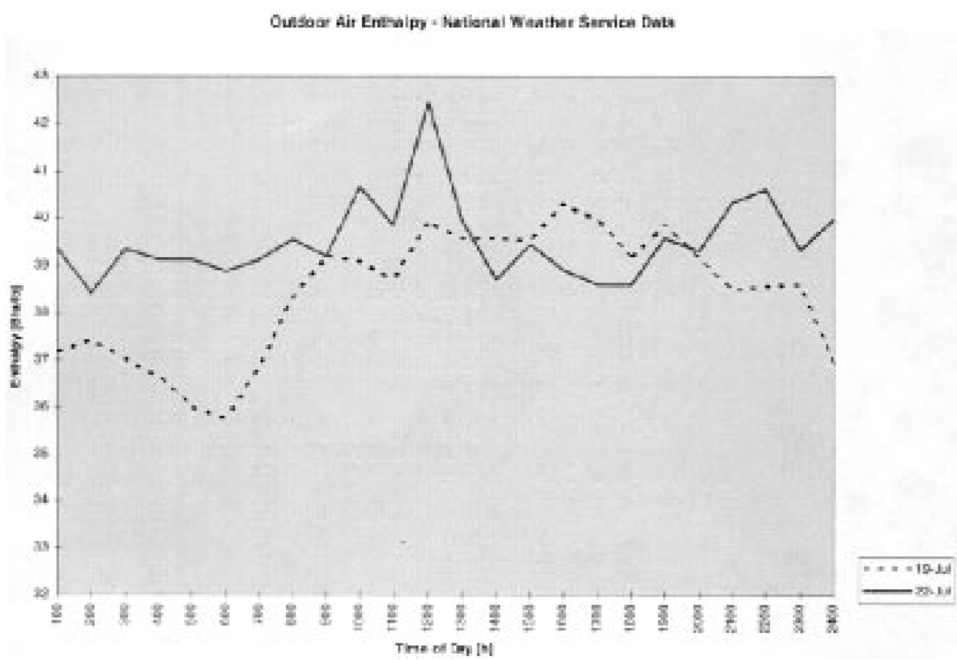
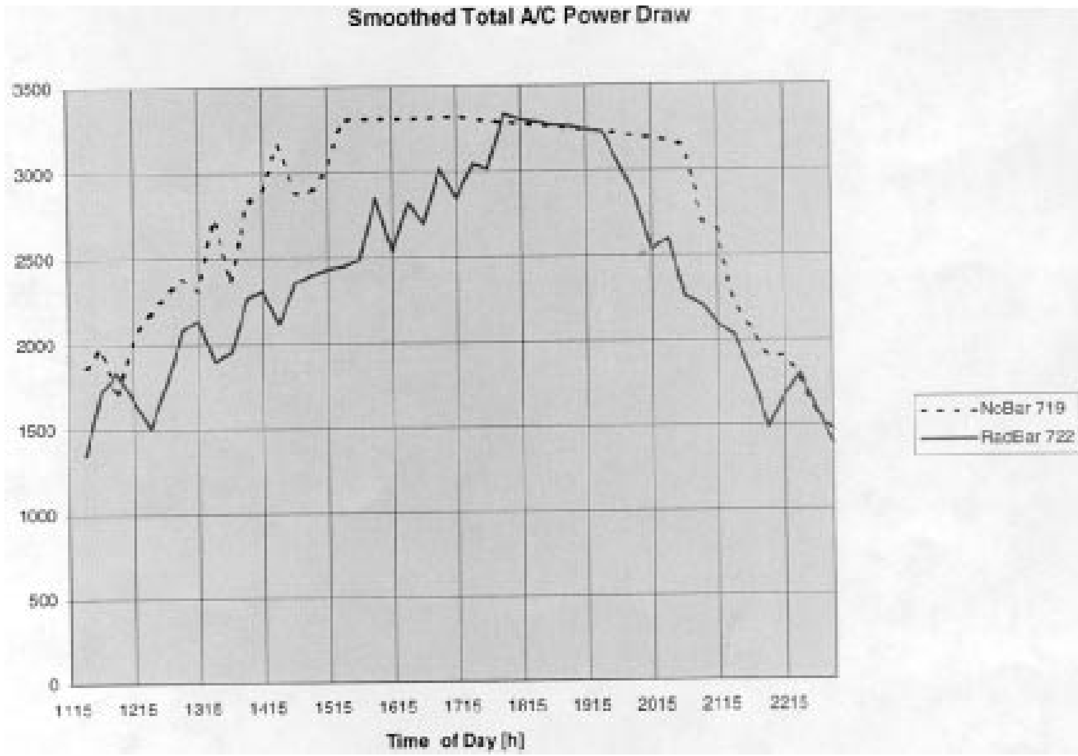


Figure 5. *Total air-conditioner electricity draw on July 19, 1995 (pre-retrofit) and July 22, 1995 (post-retrofit)*



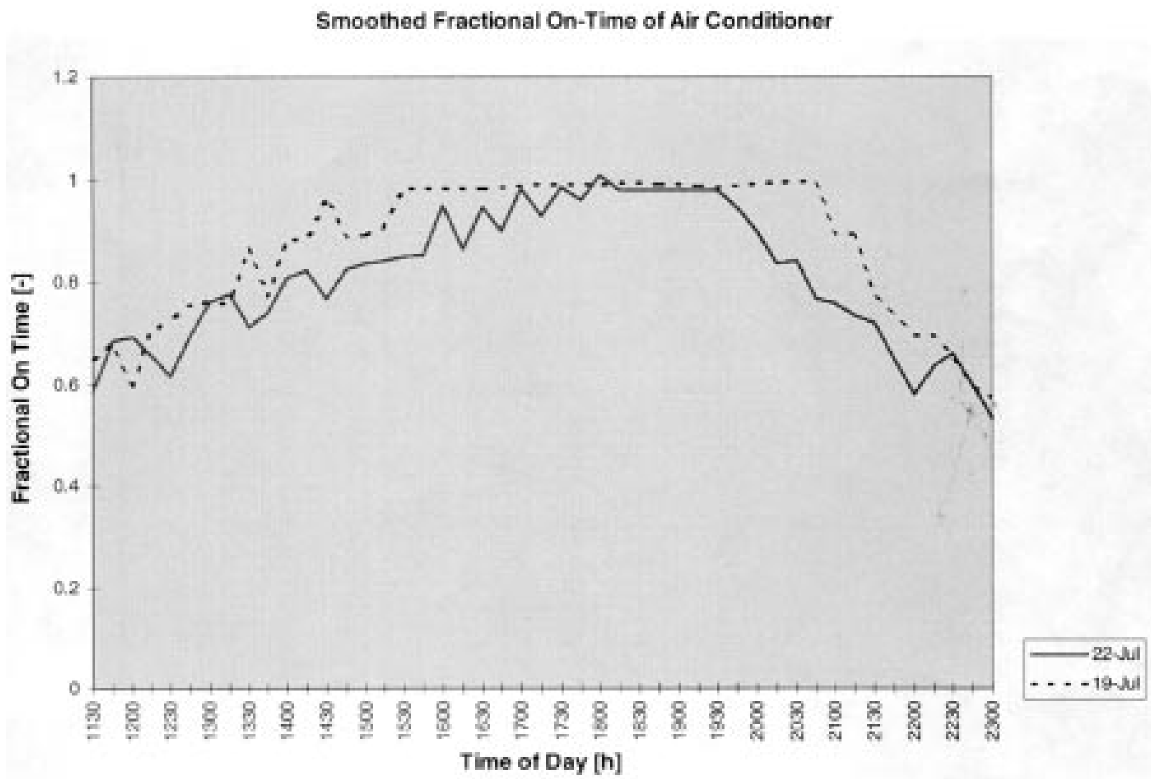
1) a higher attic ventilation rate, 2) improved heat removal at the outside surface of the roof shingles, and 3) a higher infiltration rate in the house. The first two effects tend to reduce the attic temperature measured after the retrofit, which causes an overestimation of the retrofit savings, whereas the third effect tends to increase the air-infiltration load seen by the building after the retrofit, which causes an underestimation of the impact of the retrofit. The magnitudes of each of these effects are quantified below by means of a simplified model of attic ventilation (Walker et al. 1995), an analysis of the impact of roof-shingle temperature on attic air temperature, and the ASHRAE calculation procedure for residential air infiltration (ASHRAE 1993). One effect of windspeed that is not included in this analysis is its impact on heat gain through vertical surfaces (i.e., windows and walls), however it should be noted that: 1) all windows were fitted with solar screens, 2) there was a 2 ft (0.6m) overhang on the two walls that receive any sun, and 3) the sun is high in the sky during the test period.

The air infiltration rates of the house pre- and post-retrofit are calculated based on the measured envelope leakage and weather data using the procedure outlined in Chapter 23 of the ASHRAE Handbook of Fundamentals (ASHRAE 1993). In using this procedure, the only piece of additional information used was the description of the area surrounding the house, which resulted in our using a shielding class of 3. The calculations performed yielded average air infiltration rates of 0.18 ACH for July 19, and 0.28 ACH for July 22.

The outdoor air enthalpies in Figure 4 were combined with calculated hourly air infiltration rates to estimate the latent loads due to air infiltration pre and post retrofit. These load calculations are based upon measurements of indoor relative humidity and indoor air temperature with a consumer-product thermometer/hygrometer device. Those measurements indicated indoor relative humidities of 55% and 50% between 1 p.m. and 7 p.m. for the pre- and post-retrofit periods respectively. The corresponding humidity ratios and enthalpies were calculated to be 0.0096 and 27.8 Btu/lb for the pre-retrofit period, and 0.0087 and 27.0 for the post-retrofit period. The difference in enthalpy is due to the difference in relative humidity, as the average monitored temperature at the return grille was essentially unchanged for that time period (73.5 °F on July 19 versus 73.6 °F on July 22). Hourly air infiltration loads based on the differences in indoor and outdoor enthalpy are compared for the two days in Figure 7.

The analysis results in Figure 7 indicate that, because of the differences in windspeed and to a much lesser extent, the difference in indoor enthalpy, the average building load due

Figure 6. *Fractional on-time air conditioner on July 19, 1995 (pre-retrofit) and July 22, 1995 (post-retrofit)*



to air infiltration is 81% greater during the post-retrofit day (3500 Btu/h versus 1950 Btu/h). This difference corresponds to 37,600 Btu of additional heat that had to be removed by the air conditioner during the post-retrofit day (24-hour period).

To put the impacts of these infiltration loads into perspective, they need to be compared with the heat gain through the ceiling and the ducts, which are the parameters that will be impacted by changes in attic temperature. Figure 8 is a plot of calculated air infiltration load (based on indoor-outdoor enthalpy differences and calculated infiltration rates), supply-duct conduction load (calculated from fractional on-time, air flow and temperature rise in supply ducts), return-duct leakage and conduction load (calculated from fractional on-time, air flow and temperature rise in return ducts), and ceiling heat load (calculated from temperature differential across R-38 ceiling insulation) for the pre-retrofit period. The data in Figure 8 indicate that both the duct loads and the air infiltration loads are significantly larger than the ceiling loads.

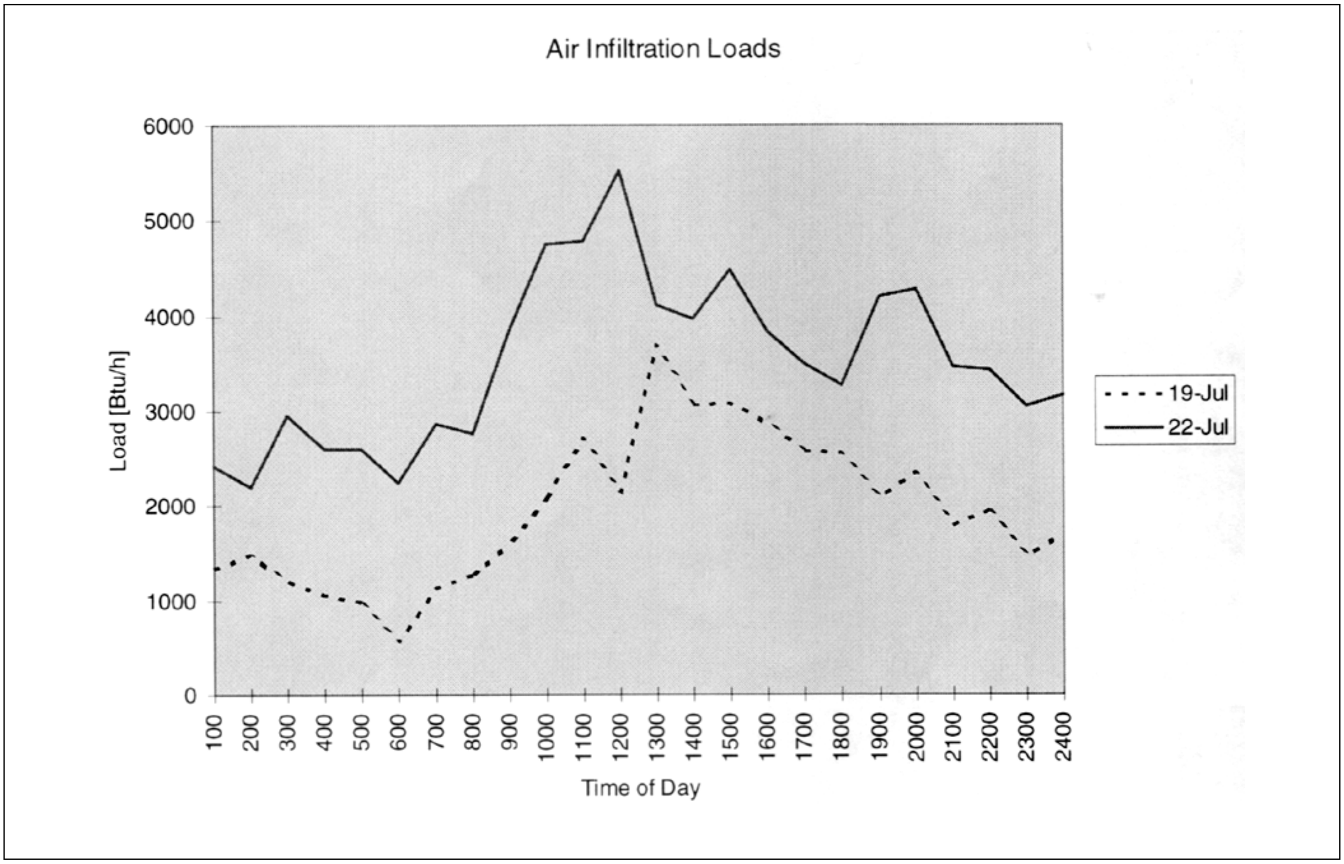
Figure 9 is a plot of the attic ventilation rate calculated based upon measured attic and outdoor temperatures, measured windspeeds, and an attic infiltration model developed by Walker et al. (1995). In using this model, a shielding coefficient of 0.5 was used to account for shielding by surrounding buildings and trees, and for the difference in height between the weather tower and the eaves of the house.

The impact of the higher windspeeds on external shingle temperatures was also examined. During the 1 to 7 PM time period, it was found that the temperature differential between the shingles and the outdoor air was on average 5 °F (or 10%) larger for the pre-retrofit period. The reductions in building load resulting from the wind-induced changes in attic ventilation rate and shingle temperatures were estimated by calculating the change in attic temperature that would be expected to occur if the windspeed during the post-retrofit period were equal to that during the pre-retrofit period. This was accomplished by assuming that the attic acts like a heater for outdoor air, with the only heat source being the heat flux across the shingles, and the only heat sink being the outdoor air passing through the attic in the form of ventilation. Making this assumption, the attic temperature can be expressed as:

$$T_{attic} = T_{out} + \frac{Q_{attic}}{\dot{m}c_p}$$

where:

Figure 7. *Air infiltration loads (sensible plus latent) on July 19, 1995 (pre-retrofit) and July 22, 1995 (post-retrofit)*



T_{attic} is the attic temperature,
T_{out} is the outdoor air temperature,
Q_{attic} is the heat flux across the shingles,
m is the ventilation rate of the attic, and
c_p is the specific heat of air.

The shingle temperature impact was calculated on an hourly basis by substituting the shingle temperatures measured on July 19 for those measured on July 22, and then calculating the change in Q_{attic} based upon the ratios of the recalculated temperature differential across the shingles to the measured values on July 22. The attic temperature impact of the change in windspeed was calculated by multiplying by the ratio of pre and post retrofit ventilation rates. The attic temperature that would have occurred if the windspeeds on July 22 were the same as those on July 19, was thus calculated as:

$$T_{atticnew} = T_{out} + (T_{attic} - T_{out}) \frac{\Delta T_{shin} + \Delta T_{19-22,shin}}{\Delta T_{shin}} \frac{\dot{m}_{post}}{\dot{m}_{pre}}$$

where:

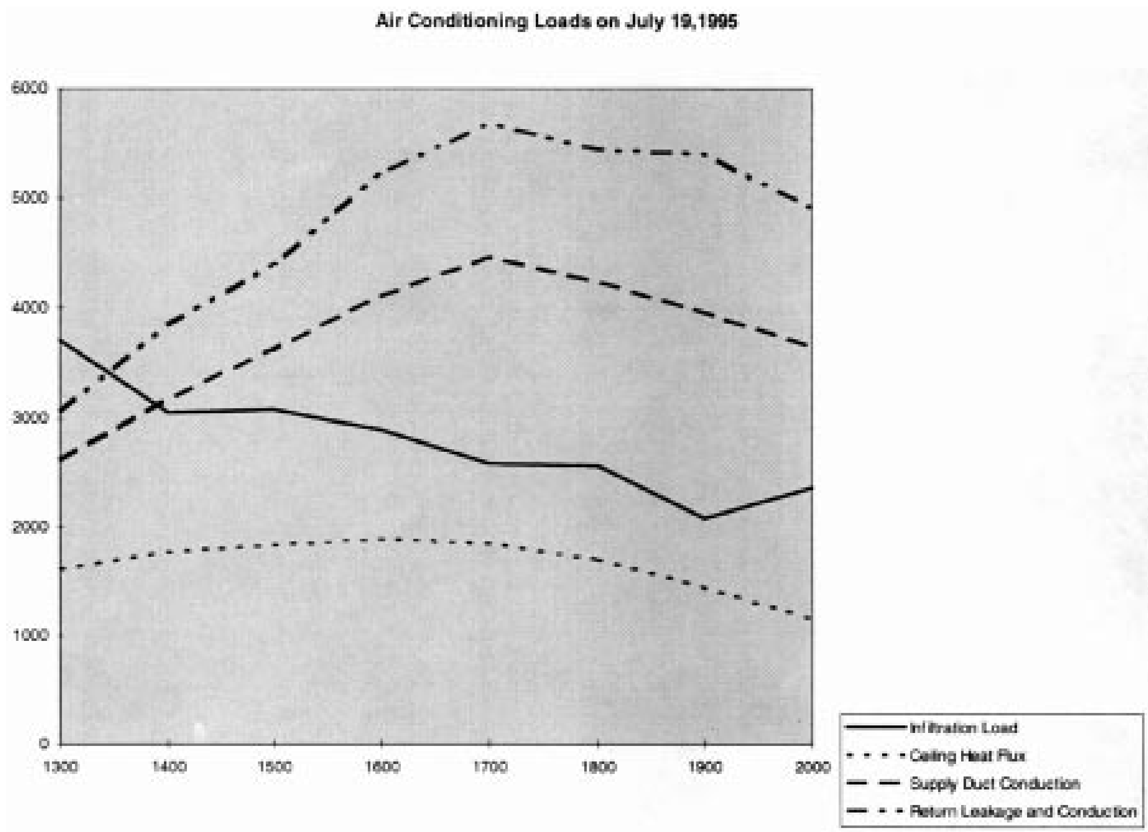
m_{pre} is the ventilation rate of the attic calculated for July 19 conditions,
m_{post} is the ventilation rate of the attic calculated for July 22 conditions,
ΔT_{shin} is the temperature differential across the shingles.
$\Delta T_{19-22,shin}$ is the shingle temperature on July 19 minus that on July 22
T_{attic} is the measured attic air temperature on July 22,
$T_{atticnew}$ is the corrected attic air temperature on July 22, and
T_{out} is the measured outdoor air temperature on July 22.

The overall change in load that would have occurred if the windspeed on July 22 were equal to that on July 19, including the impact on air infiltration, and that resulting from the higher attic temperature was calculated as:

$$L_{add} = L_{sduct} \frac{T_{atticnew} - T_{sduct}}{T_{attic} - T_{sduct}} + L_{rduct} \frac{T_{atticnew} - T_{rduct}}{T_{attic} - T_{rduct}} + L_{ceiling} \frac{T_{atticnew} - T_{ceiling}}{T_{attic} - T_{ceiling}} - \Delta L_{\inf}$$

where:

Figure 8. *Comparison of calculated July 19, 1995 (pre-retrofit) cooling loads due to air infiltration, ceiling heat flux, supply-duct conduction, and return-duct leakage and conduction*

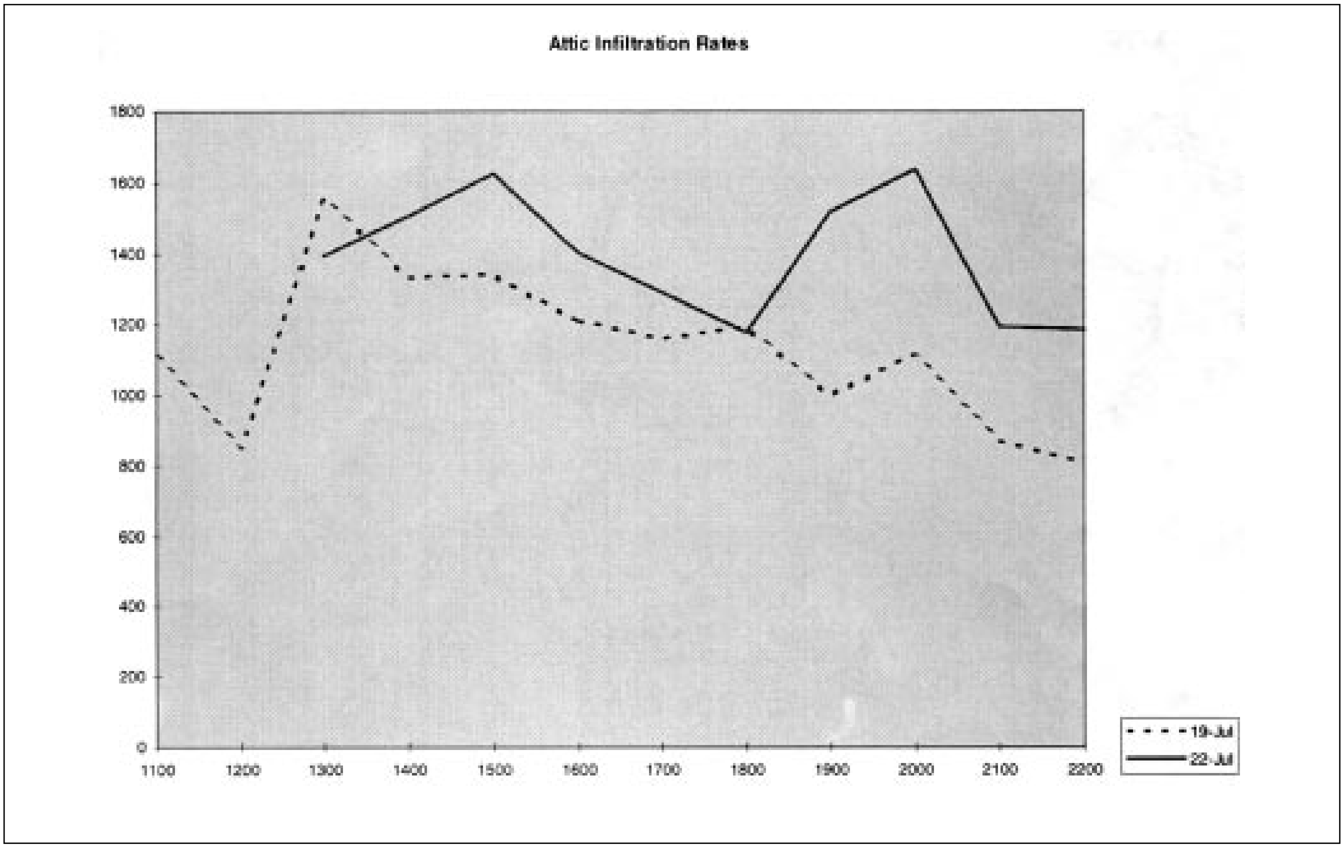


L_{add} is the calculated increase in air conditioning load on July 22 that would occur if the windspeed had been equal to that on July 19,
L_{sduct} is the uncorrected energy lost from the supply ducts,
L_{rduct} is the uncorrected energy lost from the return ducts,
$L_{ceiling}$ is the uncorrected energy flux across the ceiling,
ΔL_{inf} is the increase in infiltration energy load between pre and post-retrofit periods,
T_{sduct} is the temperature in the supply ducts, and
T_{rduct} is the temperature in the return ducts.

Based upon the above equation, the overall impact of the higher windspeed on July 22 was calculated. The average net impact of the higher windspeed on July 22 was to increase the building load for the time period between 1 PM and 7 PM by 640 Btu/h (190 W) on average. In other words, this analysis says that if the windspeed on July 22 was equal to that on July 19, the load would be 640 Btu/h (190 W) lower on average. This suggests that the energy and electricity demand savings determined from Figures 5 and 6 are conservative. This also suggests that the increased windspeed on July 22 did not have a dramatic impact on the energy consumption, as the decrease in attic temperatures associated with the increase in windspeed is offset by an increase in infiltration loads with the higher windspeed. Using the fractional on-times in Figure 6 and the nominal capacity of the air conditioner, this additional load corresponds to 2% of the total load, and therefore of the HVAC energy demand/consumption.

The calculated impact of the radiant barrier on several components of the building cooling load (including windspeed corrections) is presented in Figure 10, which also includes total hourly corrections to the building load that were used to estimate the energy consumption on July 22 that would have occurred if the windspeeds were the same as those on July 19. It is worth noting that the calculated load savings are all made smaller by the windspeed correction, but that these corrections are more than compensated for by the required correction for higher air infiltration rates after the retrofit. It is also clear that the maximum load reduction due to the radiant barrier is significant, the largest savings being

Figure 9. Calculated attic infiltration (ventilaton) rates on July 19, 1995 (pre-retrofit) and July 22, 1995 (post-retrofit)



4500 Btu/h at 5 PM, and that three quarters of the observed load reduction is associated with reduced duct-system heat gains.

Impact of Radiant-Barrier Sheathing on Attic Air Temperature

The impact of the sheathing-mounted radiant barrier on the attic air temperature was calculated with and without applying correction factors for the difference in windspeed between July 19 and July 22. The average attic temperature between 12 noon and 8 PM was 120.6 °F on July 19 (i.e., before the retrofit), and on July 22 (i.e., after the retrofit) was measured to be 100.2 °F, which when corrected to correspond to the July 19 windspeeds was 102.2 °F. This implies that the sheathing retrofit reduced the attic temperature by approximately 18 °F. Similarly, the retrofit reduced the peak attic temperature (occurring between 3 and 4 PM) from 125.7 °F to 104.3 °F (including windspeed correction), which represents a 21 °F reduction.

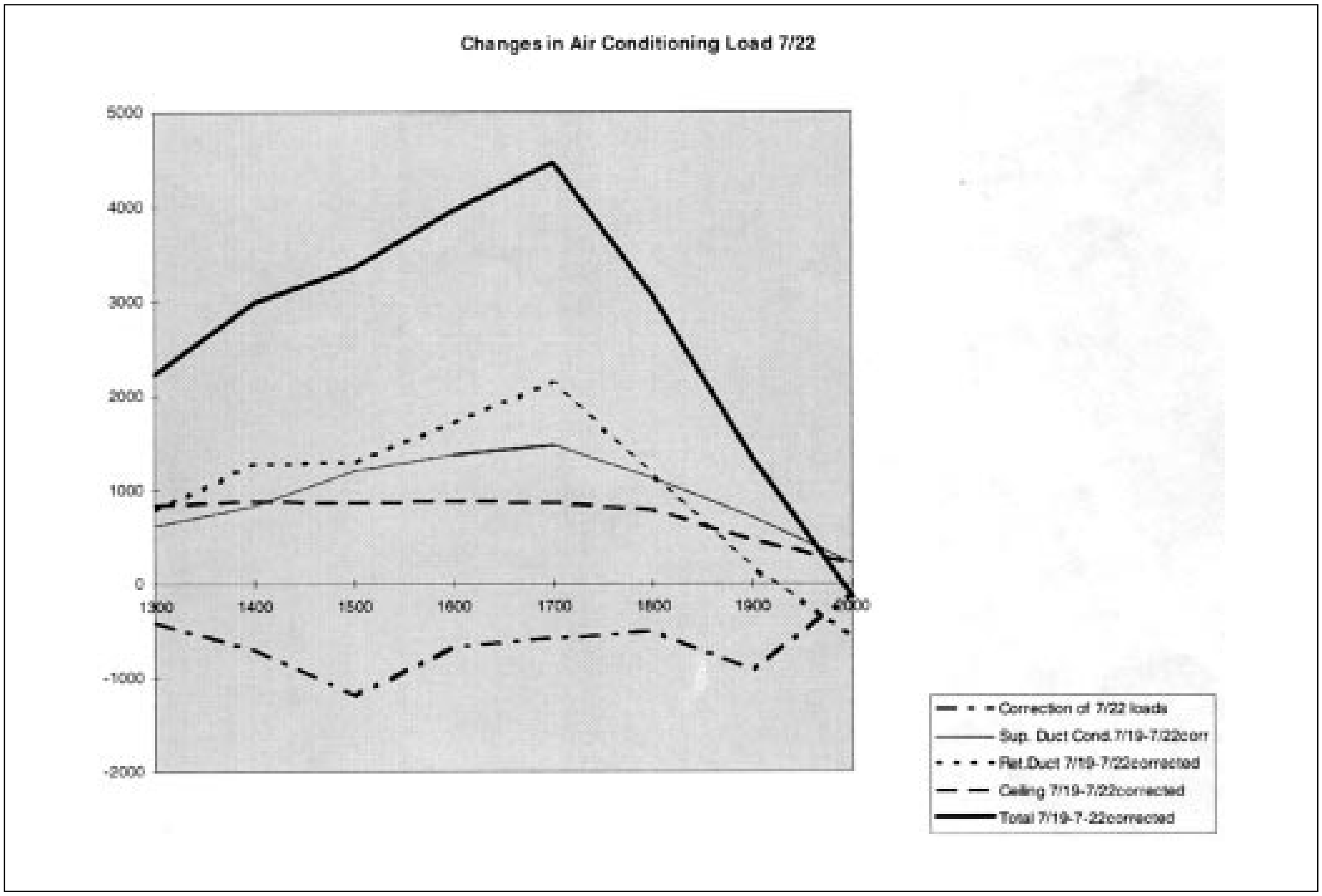
Impact of Radiant-Barrier Sheathing on Supply-Duct Conduction Losses

The impact of the radiant-barrier sheathing on the temperature rise in the supply ducts is presented in Figure 11. The numbers presented are an average for the entire duct system, with the losses in each branch of the duct system being weighted by the fraction of the supply air flow passing through that duct, and do not include a correction of the measured losses to account for the difference in windspeed. The results in Figure 1 show that the supply-duct conduction losses are reduced from approximately 16% of the equipment capacity to 12% by the retrofit, or in other words, supply-duct conduction losses are reduced by approximately 30%. This reduction corresponds to a reduction in the maximum load associated with supply-duct conduction of approximately 1500 Btu/h, the average reduction being 900 Btu/h between 1 PM and 8 PM.

Impact of Radiant-Barrier Sheathing on Return-Duct Leakage and Conduction

The impact of the radiant-barrier sheathing on the temperature rise in the return duct is presented in Figure 12. On the return side, not enough measurements were taken so as to allow a separation of the impacts of the radiant-barrier sheathing on leakage and conduction (leakage on the return side changes the return-plenum air temperature, whereas on the supply side air leakage has a minimal effect on supply-register temperatures). The results in Figure 12 show that

Figure 10. *Calculated reductions in supply-duct conduction, return-duct leakage plus conduction, ceiling, and total cooling loads due to the radiant barrier, as well as calculated changes in total July 22, 1995 (post-retrofit) air conditioning loads used to estimate the loads that would have occurred under July 19, 1995 (pre-retrofit) weather conditions*



the return-duct losses are reduced from approximately 20% of the equipment capacity to 15% by the retrofit, or in other words, return-duct losses are reduced by approximately 25%. This corresponds to a reduction in the maximum load associated with return-duct losses of approximately 2100 Btu/h around 5 PM, the average reduction being 1000 Btu/h between 1 PM and 8 PM, but does not include a correction of the measured losses to account for the difference in windspeed between July 19 and July 22.

Impact of Radiant-Barrier Sheathing on Ceiling Heat Flux

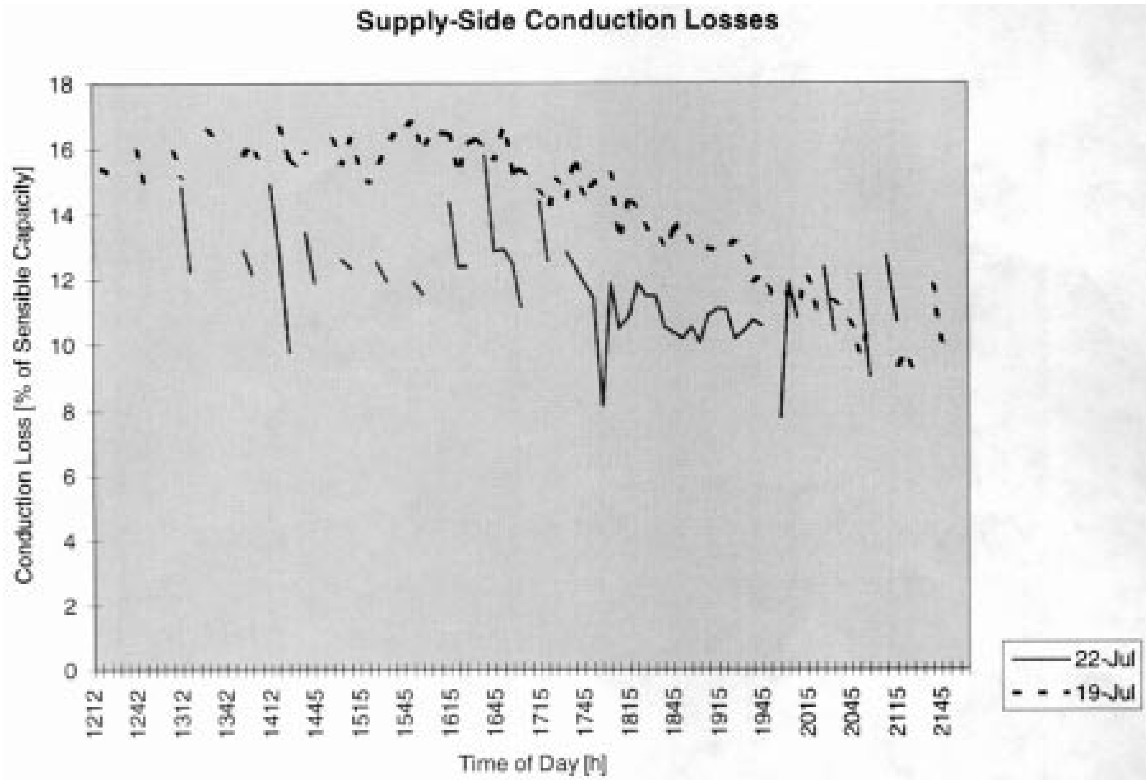
The impact of the radiant-barrier sheathing on the heat flux across the ceiling was calculated using a steady-state model of conduction across the ceiling insulation and sheetrock. The results of this calculation indicate that the ceiling heat flux is reduced by an average of 700 Btu/h between 1 PM and 8 PM, with a maximum load reduction of 900 Btu/h at 4 PM. Once again, these numbers do not include a correction of the measured losses to account for the difference in windspeed between July 19 and July 22.

DISCUSSION

Several issues surrounding the above results merit some discussion, including: 1) a comparison with results from other studies, 2) the breakdown of the contributing components of the savings, and 3) the potential ramifications of the observed capacity increase for standard equipment-sizing decision tools.

Most other studies have focused on the impacts of radiant barriers on ceiling heat flux, which, based upon our component-by-component breakdown of the savings, represents only 20% of the observed radiant-barrier impact on HVAC electricity consumption in this study. We compared the percentage change in ceiling heat fluxes resulting from the addition of our roof-sheathing radiant barrier with those measured by Fairey (1985) for a roof-mounted radiant barrier

Figure 11. *Comparison of flow-weighted supply-side conduction losses on July 19, 1995 (pre-retrofit) and July 22, 1995 (post-retrofit)*



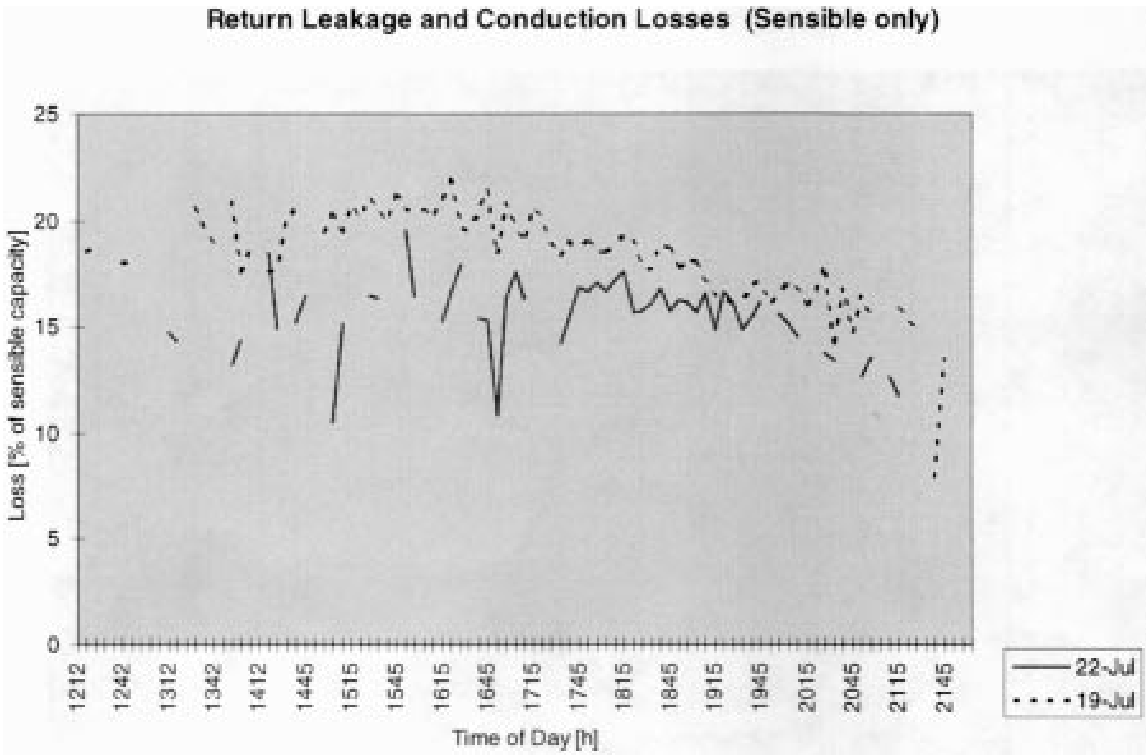
installed with the low emissivity surface facing down in a well-vented attic with R-19 ceiling insulation. Our tests indicated a 44% reduction in ceiling heat flux due to the addition of the radiant barrier, whereas the Fairey data indicated a 43% reduction in the ceiling flux.

The impact of the retrofit on the efficiency of the equipment (i.e., higher temperatures surrounding the air handling unit and the coil) is not included in our breakdown of losses or corrections. Because the air handling unit and the evaporator coil were both located within the attic, the efficiency of the air conditioner should be increased somewhat by the lower attic temperatures after the retrofit. On the other hand, this effect is mitigated by the fact that the air conditioner is not cycling during the hot part of the day, particularly during the pre-retrofit period. The impact of high surrounding temperatures on the equipment is generally much larger for equipment that is cycling due to the relatively small surface area and relatively high thermal mass of the air handling unit. Also, because the effective capacity of the HVAC system is increased by the retrofit, the cycling of the equipment is also increased, resulting in a lower equipment efficiency. Finally, the equipment efficiency should be lower after the retrofit because the air entering the coil is cooler.

Based upon the analysis presented above, the installation of a radiant barrier should impact HVAC equipment sizing. Manual J of the Air Conditioning Contractors of America (ACCA) association is the industry-standard design-load calculation procedure for residences (ACCA 1986). Unfortunately, this manual does not currently address the impacts of radiant barriers on building loads, nor their impact on duct-system performance.

Relative to duct performance, Manual J provides a table of duct-loss multipliers that are used to calculate the extra design load associated with conduction losses from the ducts, however the duct loss multipliers for an attic and a crawlspace are the same, which is clearly inconsistent with intuition and field experiments. The result is that equipment with attic ductwork is likely to be relatively undersized as compared to equipment with crawlspace ductwork. Moreover, these duct-loss multipliers do not account for technologies that change the attic air temperature, such as radiant barriers or high-reflectivity shingles, nor do they take into account thermal transfer through ducts during the off-cycle (Modera and Treidler 1995), the impacts of duct leakage on their performance, or the impacts of duct surface area or length on heat gains or losses. Depending on the geometry of the

Figure 12. *Comparison of return side conduction and leakage (sensible only) losses on July 19, 1995 (pre-retrofit) and July 22, 1995 (post-retrofit)*



system, duct thermal exchange due to thermosiphon flows during the off-cycle can be significant (Modera and Treidler 1995), and would be impacted by attic air and radiant temperatures.

CONCLUSIONS

Several conclusions can be drawn based upon the data presented. First, our results suggest that the energy savings potential, as well as the potential for reducing maximum cooling load, associated with adding a radiant barrier to roof sheathing is significant, at least for a house that has ductwork and/or an air-handling unit installed in the attic. Based upon pre- and post-retrofit data from two comparable days, the radiant barrier reduced daytime air-conditioner electricity consumption by 16%, and reduced air conditioning load by as much as 4500 Btu/h (or 15% of nominal capacity). Moreover, this savings is observed in a new well-insulated house with R-38 ceiling insulation. Another conclusion to be drawn from the data presented is that the majority of the savings associated adding a radiant barrier to such a house stems from reducing the heat gain of the air distribution system installed in the attic. Approximately 80% of the observed savings is realized as a result of reduced heat gain by the HVAC system. Finally, the observed reduction in the maximum cooling load seen by the HVAC system suggests that the impacts of attic radiant barriers need to be taken into account when sizing HVAC equipment, at a minimum when the HVAC system is located in the attic.

REFERENCES

ASHRAE 1993. *ASHRAE Handbook of Fundamentals, Chapter 23*. Atlanta, GA. American Society of Heating, Refrigerating and Air Conditioning Engineers.

ACCA 1986. *Manual J: Load Calculation for Residential Winter and Summer Air Conditioning, Seventh Edition*. Washington, D.C. Air Conditioning Contractors of America.

CEC 1995. *1993 Residential Field Data Project: Energy Characteristics, Code Compliance and Occupancy of California 1993 Title-24 Houses*. CEC Contract 400-91-031. Sacramento, Calif. California Energy Commission. April 30.

Fairey, P. 1985. *The Measured Side-by-Side Performance of Attic Radiant Barrier Systems in Hot Humid Climates*. FSEC-PF-111-86. Cocoa, Flor. Florida Solar Energy Center.

Fairey, P. 1990. *Seasonal Prediction of Roof-Mounted Attic Radiant Barrier System Performance from Measured Test Data*. FSEC-PF-237-90. Cocoa, Flor. Florida Solar Energy Center.

LCRA 1995. *1995 Good Cents Home Specifications for HVAC Rebates*. Austin, Texas. Lower Colorado River Authority.

Levins, W.P., and M.A. Karnitz. 1986. *Cooling-Energy Measurements of Unoccupied Single-Family Houses with Attics Containing Radiant Barriers,* ORNL/CON-200, Oak Ridge, Tenn. Oak Ridge National Laboratory. July.

Levins, W.P., and M.A. Karnitz. 1987. *Heating Energy Measurements of Unoccupied Single-Family Houses with Attics Containing Radiant Barriers,* ORNL/CON-213, Oak Ridge, Tenn. Oak Ridge National Laboratory. January.

Levins, W.P., and M.A. Karnitz. 1987a. *Cooling Energy Measurements of Single-Family Houses with Attics Containing Radiant Barriers in Combination with R-11 and R-30 Ceiling Insulation,* ORNL/CON-226, Oak Ridge, Tenn. Oak Ridge National Laboratory. May.

Levins, W.P., and M.A. Karnitz. 1988. *Heating Energy Measurements of Single-Family Houses with Attics Containing Radiant Barriers in Combination with R-11 and R-30 Ceiling Insulation*, ORNL/CON-239, Oak Ridge, Tenn. Oak Ridge National Laboratory. August.

Levins, W.P., M.A. Karnitz, and J.A. Hall. 1989. *Moisture Measurements in Single-Family Houses with Attics Containing Radiant Barriers,* ORNL/CON-255, Oak Ridge, Tenn. Oak Ridge National Laboratory. February.

Luciani, F., 1992. ''Builders Perspective on Duct Systems in Houses,'' *Proceedings of the DOE Industrial Thermal Distribution Conference*, BNL-52341. Upton, NY. Brookhaven National Laboratory.

Modera, M.P. and E.B. Treidler. 1995. ''Improved Modelling of HVAC System/Envelope Interactions in Residential Buildings.'' *Proceedings of ASME International Solar Energy Conference,* March 19–24. American Society of Mechanical Engineers. Lawrence Berkeley Laboratory Report LBL-36048.

Walker, I.S., T.W. Forest, and D.J. Wilson. 1995. ''A Simple Calculation Method for Attic Ventilation Rates.'' *Proceedings of the 16th AIVC Conference*, *Implementing the Results of Ventilation Research,* vol. 1: 221–231. Palm Springs, Calif. September 19–22. Air Infiltration and Ventilation Centre.