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Effects of Radiant Barriers and Attic Ventilation on Residential Attics and Attic Duct Systems: New Tools for Measuring and Modeling

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ABSTRACT

A simple duct system was installed in an attic test module for a large-scale climate simulator at a U.S. national laboratory. The goal of the tests and subsequent modeling was to develop an accurate method of assessing duct system performance in the laboratory, enabling limiting conditions to be imposed at will and results to be applied to residential attics with attic duct systems.

Steady-state tests were done at a severe summer condition and a mild winter condition. In all tests the roof surface was heated above ambient air temperatures by infrared lights. The attic test module first included then did not include the duct system. Attic ventilation from eave vents to a ridge vent was varied from none to values achievable by a high level of power ventilation. A radiant barrier was attached to the underside of the roof deck, both with and without the duct system in place. Tests were also done without the radiant barrier, both with and without the duct system. When installed, the insulated ducts ran along the floor of the attic, just above the attic insulation and along the edge of the attic near the eaves and one gable.

Air temperatures were measured from the ridge to the insulation surface along the center of the test module at all ventilation rates. For all tests, air temperatures inside the ducts, as well as attic air, attic insulation, and gable and deck temperatures, were measured and compared to the predictions of the model. Only average attic air temperatures were compared since the model did not include stratification. The ducts were placed along the eaves in the test module. This is thought to exacerbate stratification in these tests more than the placement of ducts in real attics would. The ducts along the eaves partially blocked the path for ventilation air to mix with attic air near the insulation between the ducts.

Despite adequate duct insulation, the duct system kept attic conditions cooler in summer and warmer in winter. Since the infrared lights were heating the roof above ventilation air temperatures at all conditions, increasing ventilation caused attic air and insulation surface temperatures to decrease. At the mild winter condition, compared to measurements with no radiant barrier attached to the underside of the deck but with the ducts installed, there was an average 37% increase in heat loss into the attic with the radiant barrier and ducts in place. This heating penalty varied randomly with ventilation rate in these tests. At the severe summer condition simulated in the tests, the radiant barrier decreased the heat gain through the ceiling. The average cooling benefit was 34% with ducts in the attic and 29% without them. Variation with ventilation rate was again random, but there was less variation than at the mild winter condition.

These tests in a climate simulator achieved careful control and reproducibility of conditions. This elucidated dependencies that would otherwise be hidden by variations in uncontrolled variables. Based on the comparisons with the results of the tests at the mild winter condition and the severe summer peak condition, model predictions for attic air and insulation temperatures should be accurate within ±10°F (±6°C). This is judged adequate for design purposes and could be better when exploring the effect of changes in attic and duct parameters at fixed climatic conditions.

INTRODUCTION

In residential air-conditioning installations in the southern United States, supply ducts for conditioned air are commonly installed in the attic. This makes for convenient and effective distribution of conditioned air within the living space during the cooling season and adequate distribution during heating if, indeed, the ducts are used for heating. However, the attic is a hostile thermal environment for the ducts. If leaks are present in the ducts and duct insulation is

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inadequate, the quantity and quality of conditioned air delivered to the living space will be far from design specifications.

A residential attic, even without a duct system installed in it, is a complicated heat transfer system. Energy effects due to thermal conduction, convection, radiation, and moisture transport directly affect conditions in the attic. Wilkes and coworkers (Wilkes and Rucker 1983; Wilkes et al. 1991a; Wilkes et al. 1991b; Wilkes and Childs 1992) built attic test modules for guarded hot boxes and programmed a detailed dynamic computer model to study the thermal performance of residential attics with various levels and types of attic insulations. Their work produced a well-characterized attic test module and validated a general attic model to provide data on the thermal performance of residential attics in a broad range of climatic conditions.

Much of the work addressed the effect of radiant barriers on attic performance. Results from the attic model used for the work reported in this paper were compared to results of steady-state experiments in the attic test module used for this work, but without ducts in either, as well as ceiling heat fluxes from field experiments with full-size houses (Wilkes 1989). Model predictions were generally within ±10% of experimental results.

The experiments showed a wide variation in the ability of a radiant barrier to reduce ceiling heat flow during summer and winter conditions. Very comprehensive field experiments used for comparisons were those in East Tennessee by Levins and Karnitz (1987, 1988). Three side-by-side unoccupied houses were monitored. A horizontal radiant barrier, placed over R_{US}-11 h·ft^2·°F/Btu (R_{SI}-1.9 m^2·K/W) ceiling insulation in the second house, reduced cooling load by 16% compared to that of the first house with no radiant barrier but the same level of insulation. A truss radiant barrier, installed in the third house with the same level of insulation, reduced cooling load by 11%. With R_{US}-30 (R_{SI}-5.3) insulation, the two types of radiant barriers yielded 2% and 0.7% cooling load reductions, respectively. A horizontal radiant barrier with R_{US}-11 (R_{SI}-1.9) insulation yielded a 9% reduction in heating load, but a truss radiant barrier showed an insignificant increase. With R_{US}-30 (R_{SI}-5.3) insulation, both types of radiant barriers showed 3.5% reductions in heating load.

Other field experiments for which predictions were compared to experiments were those of Ober and Volckhausen (1988) in side-by-side spaces of the attic in a house in Florida. On one side the nominal R_{US}-19 (R_{SI}-3.3) fiberglass batt insulation was augmented by a radiant barrier draped between the rafters. Both sides were vented naturally, but there was a complicated interaction of the ventilation airflow in the space between the radiant barrier and the roof and the flow in the main attic space. This draped radiant barrier showed weekly measured heat gain reductions of about 21%.

In more recent work by Wilkes and Childs (1993), the attic test module and attic model used for this paper were used to document the thermal performance of clean horizontal radiant barriers under nighttime or low solar gain winter conditions. A highly reflective horizontal radiant barrier over the top of the insulation decreased ceiling heat flow through the R-22 to 25 h·ft^2·°F/Btu (3.9 to 4.4 m^2·K/W) ceiling insulation by 6% to 8% compared to heat flow with the same ceiling insulation but without the radiant barrier. The model predicted this reduction within experimental uncertainty.

We found few published data on the effect of ducts in attics on attic performance. One example is from a study by Levins and Herron (1990) of occupied houses in Georgia with insulated ducts in R_{US}-11 (R_{SI}-1.9) insulated attics. Using statistical analysis of data from side-by-side houses, one without and the other with a radiant barrier under the ducts and on top of the attic insulation, they concluded that a horizontal radiant barrier yielded about 17% adjusted annual cooling savings and 11% adjusted annual heating savings. This is nearly the same effect Levins and Karnitz found in the East Tennessee houses. No specific effect of the ducts was noted in the conclusions for the Georgia houses.

This paper extends the experiments with Wilkes' attic test module and presents details about his attic model and its use to predict results from experiments for the effect of a duct system in the attic test module. Steady-state tests simulate severe summer peak cooling and mild winter daytime heating, respectively. The duct system was attached to an independently controllable supply of conditioned air, cooled and reheated for summer conditions by a small air conditioner and duct air heater and heated for winter conditions by the duct air heater. The air supplied to the ducts was recirculated at a thermostatically controlled constant temperature with no humidity control. For the results in this paper the insulated duct system was operated with no deliberate leaks. Results of the tests with leaks are reported elsewhere (Gu et al. 1996).

In tests both with and without the duct system, attic ventilation was varied from none to very high levels achievable only by power ventilation, first with no radiant barrier under the roof deck and then with a radiant barrier attached to the underside of the deck. In all tests, conditions were monitored in and around the attic test module and the duct system, when installed, for comparison to the predictions of the attic model. Only one level of attic insulation, about R-12 h·ft^2·°F/Btu (2.1 m^2·K/W), was used in the experiments to ensure a significant effect of the radiant barrier and duct system on heat transfer through the ceiling. The results of each test documented the actual R-value of the ceiling insulation for the test.

EXPERIMENTAL FACILITY

Large-Scale Climate Simulator

The tests were done in a large-scale climate simulator (LSCS) at a U.S. national laboratory. The LSCS, shown schematically in Figure 1, provides controlled conditions of temperature and humidity above and below test sections with dimensions exposed to the guard chamber as large as 12.5 ft by 12.5ft (3.8 m by 3.8 m). A test section, such as the residential attic test module that is shown in place in the LSCS, is assem-

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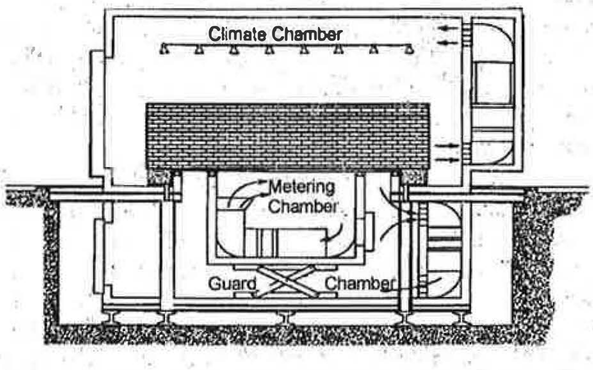

Figure 1 *Schematic of the large-scale climate simulator with the residential attic test module inside the climate chamber.*

bled in a diagnostic platform outside the LSCS and moved by a crane. An assembly can weigh as much as 10 tons (9100 kg) and can be 6 ft (1.8 m) high. Once a test section is in place with all instrumentation installed, an automated data acquisition and control system maintains desired conditions above and below it and records the responses of thermocouples and resistance temperature devices, heat-flux transducers, relative humidity sensors, mass flow rate meters, load cells, pressure transducers, anemometers, current shunts, or any transducer that produces a voltage output.

The upper, or climate, chamber simulates climatic conditions of interest for testing thermal performance: steady-state temperatures from 150°F to –40°F (66°C to –40°C) and a wide range of relative humidities (dew point temperature is controllable from 37°F to 122°F or 3°C to 50°C). Infrared lamps can heat surface temperatures to 200°F (93°C). There is sufficient heating and refrigerating capacity to vary the simulated outdoor conditions in diurnal cycles, which allows tests of the dynamic response of test sections. For the tests done here, steady-state conditions were sought typical of a severe summer and mild winter day. The set points for the summer tests were a roof temperature near 150°F (66°C) with air temperature near 110°F (43°C). For the winter tests, they were a roof temperature near 55°F (13°C) with air temperature near 20°F (–7°C). A thermocouple under a shingle near the top of the attic test module roof was used to control the temperature to which the roof was heated with infrared lights separately from the control of air temperature in the climate chamber.

The lower, or guard, chamber temperature can be controlled from 40°F to 150°F (4°C to 66°C) and its dew point temperature can be controlled over the same range as in the climate chamber. With the metering chamber lowered, the guard chamber provides steady temperature and relative humidity conditions to simulate indoor conditions below multiple panels, typically four to nine rectangular-shaped constructions. Construction features of the panels can be varied and the effect of different features tested simultaneously. With the metering chamber in place against the bottom of a single panel test section, such as the attic test module, temperatures from 40°F to 150°F (4.4°C to 66°C) can be held below the 8 ft by 8 ft (2.4 m by 2.4 m) metered area. The heat flow across the metered area is determined by an energy balance on the metering chamber. Its precision has been documented to be better than ±3% and its bias less than ±5% (Wilkes et al. 1996).

Residential Attic Test Module

Figure 2 is a three-dimensional schematic of the residential attic test module to complement the side view of it in place inside the climate chamber in Figure 1. The module simulates a gabled attic typical of residential construction. Overall dimensions are 14 ft by 16 ft (4.3 m by 4.9 m) with a ceiling that is approximately 12.5 ft by 14.5 ft (3.8 m by 4.4 m). Ceiling area is, therefore, about 180 ft² (16.8 m²). Nominal 2×4 wood joists and rafters, 24 in. (0.61 m) on centers, form the framing. Ridge to insulation height was 3 ft (0.9 m) in these tests, yielding an attic volume of approximately 540 ft^3 (15.3 m^3). The 5 in 12 slope roof comprises 0.5 in. (1.3 cm) thick plywood nailed to the rafters and covered by roofing felt and medium gray asphalt shingles. The ceiling is 0.5 in. (1.3 cm) thick gypsum board. The gables are 0.5 in. (1.3 cm) plywood. The gable vents shown in Figure 2 were covered by foam insulation and sealed with tape for the tests described in this paper and only the soffit-ridge vent system was used.

Attic ventilation is controllable from 0 to about 2.5 cfm/ft² (0.76 m^3/min per m²) of attic ceiling area by a blower and dampers. Air enters through the soffit vents and exits through the ridge vent. Hot-wire anemometers measure the total flow rate into the plenum under the soffit on each side. Cardboard baffles under the rafters near the eaves prevent insulation from blocking the soffit vents and prevent ventilation air from blowing directly through loose-fill insulation.

In preparation for these tests, loose-fill fiberglass insulation was blown into the attic. Our blowing technique produced an uncompressed insulation density of 0.61 lb/ft^3 (9.8 kg/m^3). Settled undisturbed depth in the center of the attic was about 6.1 in. (15.5 cm), but the insulation was disturbed by several

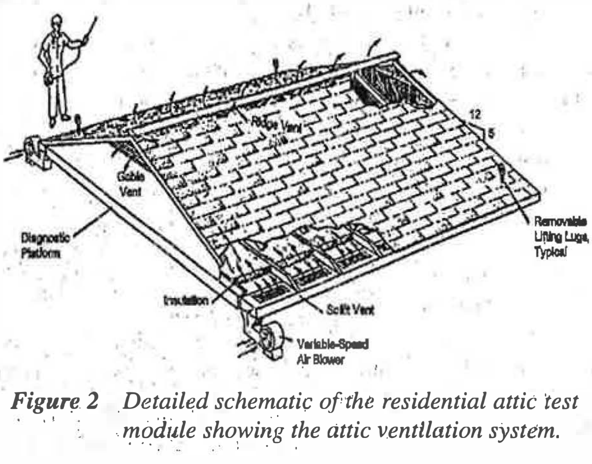

Figure 2 *Detailed schematic of the residential attic test module showing the attic ventilation system.*

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installations and removals of the duct system and the installation of the radiant barrier. The effects of these disturbances are reflected in the actual R-values of the insulation, including the ceiling under it, which were measured in each test. Based on the temperature difference observed for the onset of free convection at winter conditions in the loose-fill fiberglass used earlier (Wilkes and Childs 1992), the critical temperature difference for the thickness and density in this study is about 35°F (19°C). The temperature differences resulting at the winter condition were from 20°F to 35°F (11°C to 19°C). Free convection in the insulation is assumed negligible.

The residential attic test module is instrumented with about 125 thermocouples to sense the temperatures throughout it. Locations include under the shingles at one gable end, at the middle, and at the other gable end in three rows on each sloped side. An extra row was added for these tests on each sloped side near the eave edge under shingles laid over the attached shingles (see Figure 3). There are thermocouples on the underside of the roof deck at one gable end, at the middle, and at the other gable end under each sloped side in a row between the upper two rows of shingle thermocouples. Other locations are on the inside and outside surfaces of the gables, at the soffit vent inlets, and along the ridge vent outlet at one gable end, at the middle, and at the other gable end. There are four thermocouples on the top of the ceiling under the insulation between joists, four directly over the joists, and four directly under the joists. Four arrays of 21 thermocouples each over the metered area report the temperatures midway between the joists for the metering chamber air, the bottom surface of the gypsum ceiling, the top surface of the insulation, and the attic air 3 in. (7.6 cm) above the insulation. The attic air and insulation surface thermocouples are attached to a wire grid held by a frame. The frame can be raised or lowered to accommodate various thicknesses of insulation. In these tests, arrays of thermocouples 3, 9, 17, 25, and 33 in. (8, 23, 43, 64, and 84 cm) down from the ridge were attached to wires suspended at five locations along the ridge to measure the extent of stratification of attic air temperatures. These thermocouples were used instead of the ones just above the insulation to indicate air temperature in the attic. Average temperatures for the metering chamber air, ceiling, attic insulation surface, and attic air were found by averaging the readings from the arrays for each. Other thermocouples in the residential attic test module were not used to free up some of the 144 thermocouple data channels for use by thermocouples installed in and around the duct system.

Attic Duct System

Figure 3 is a photograph of the residential attic test module with the north gable removed. The attic test section is oriented in the climate chamber with the ridge running north and south. The south gable is next to the air handler for the climate chamber shown at the right side of Figure 1. The duct system inside the attic consists of lengths of duct along both eaves of the test module and across one gable end. Four foot (1.2 m) sections of 6 in. (15.2 cm) diameter galvanized duct were screwed and taped together and the assembly suspended by hangers fastened to the rafters. When the photograph was taken, the ducts were uninsulated. The length of duct along the east side of the module (the left side in the photograph) was connected to the outlet of the HVAC system for the ducts. The connection was made through a hole in the south gable. This duct ran the length of the test module just inside the area over the metering chamber. The cross piece seen in Figure 3 ran across the width of the test module just inside the north end and outside the area over the metering chamber. Another length of duct like the one connected to the HVAC system outlet ran along the test module just inside the area over the metering chamber on the west side. It was connected to the return of the HVAC system through another hole in the south gable. Tests were done on the effect of leaks in the uninsulated duct (Gu et al. 1996). After those tests, the uninsulated duct system was removed from the test module, insulated outside the climate chamber, and reinstalled for more tests on the effect of leaks and for these tests. Foil-covered fiberglass batt duct insulation was cut to wrap loosely around the duct. Foil-faced duct tape covered the seams along the duct and between pieces of the insulation.

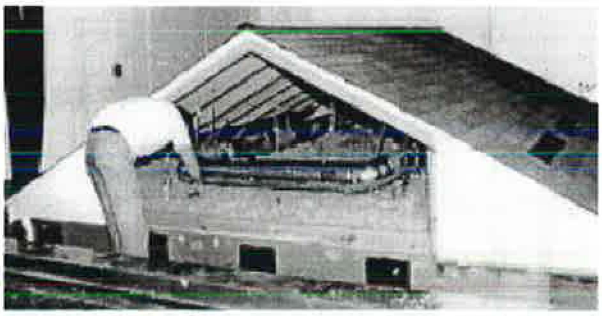

Figure 3 *Photograph of the residential attic test section with the uninsulated attic duct system suspended from the rafters.*

Thermocouples, hot wire anemometers, and pressure sensors were added to the attic test module to measure the temperatures in and around the ducts, airflow rate into and out of the duct system, and static and total pressures in the ducts. Figure 4 shows the instrumentation added for the duct system. The thermocouple arrays for average temperature at the eight locations shown from the inlet to the exit of the duct system each consisted of five thermocouples. Each thermocouple at a location was placed in the middle of equal-area segments of the circular duct along wires strung across the duct in a cross pattern. The five in each array were connected in parallel to produce directly the average temperature at the location from a single channel of data acquisition. Thermocouples for surface temperatures were attached with foil-covered duct tape. Thermocouples for air temperatures outside the duct were radiation shielded with a small piece of aluminum foil-faced tape covering each thermocouple measuring junction.

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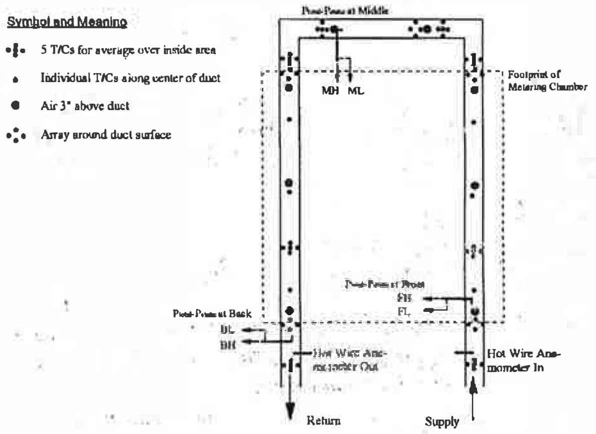

Figure 4 *Location of hot wire anemometers, pitot probes, and thermocouples in the duct system added to the residential attic test module.*

Calibration factors in the flow computer/transmitter for the hot wire anemometers at the inlet and exit of the duct system were adjusted to report the average duct velocity. The average velocity at room temperature was measured occasionally by inserting a pitot probe for a top-to-bottom and side-to-side traverse of the duct before the elbow at the end of the duct run from the air supply. Pitot probes were mounted throughout the tests at the centerline of the duct near the front, middle, and back of the duct system. Plastic hose was run outside the climate chamber from their total and static pressure taps to two pressure transducers for each probe, yielding total and static pressures relative to atmospheric pressure at each location. The pressure data were obtained in support of the work by Gu et al. (1996).

ATTIC MODEL

The program ATICSIM models a gabled attic having a five-sided cross section. At least two input files are needed: a description of the geometric and thermal characteristics of the attic and an hourly listing of weather data. The geometric/thermal characteristics file has options for trusses and ducts in the attic as well as moisture sorption/desorption. Only the duct option was used in this study. Weather data processed from weather tapes, such as Typical Meteorological Year (TMY) data, are needed for dynamic modeling. For comparison to the results of the steady-state tests in the LSCS, exterior surface temperatures were specified from the tests.

When using complete TMY weather data and an input constant interior temperature below the ceiling, ATICSIM calculates the heat flux through the ceiling, the temperatures of all exterior and interior surfaces of the ceiling, and the five sides of the structure over the attic as well as the ventilation rate corresponding to the amount of vent openings. The program can impose exterior or interior temperatures for a particular surface or hold a specified ventilation rate during the simulation. To account for the effect of using the infrared lights and to avoid the need to estimate film coefficients on the exterior surfaces and the ceiling of the attic test module, all exterior surface temperatures and the ceiling temperature were set to the measured values. The measured ventilation rates and ventilation air temperatures were also used as inputs.

Other input data were provided to model the attic test module with its simple duct system. The required thermal characteristics of the ceiling and the five sides of the attic facing the climate chamber were greatly simplified by the steady-state conditions. Only the surface-to-surface thermal conductances were required. For the ceiling, the inverse of the R-value measured in the experiments was used. For the other components, estimates of thermal conductance were generated from a physical description of the components and data in *ASHRAE Fundamentals* (ASHRAE 1993a), yielding conductances of 1.20 Btu/h·ft²·°F (6.8 W/m·K) for the roof and 2.13 Btu/h·ft²·°F (12.1 W/m·K) for the gable and eave walls. Companion programs are available to generate conductive transfer functions based on constituent thickness, thermal conductivity, and heat capacity and density for each layer making up a particular component of the attic envelope. Two distinct thermal paths with specified framing fraction are allowed for each. The output of the companion programs is exactly the input needed to describe the thermal characteristics of each component in ATICSIM for dynamic modeling.

The solar absorptances and infrared emittances of the exterior surfaces are required in the input file. Typical values of 0.9 were input, but their effect was overridden by the measured exterior temperatures. The infrared emittances of the inside surfaces of the attic enclosure are also required. Values of 0.9 were used for all surfaces except the radiant barrier. For the cases wherein a radiant barrier was installed on the underside of the deck, the infrared emittance was lowered to 0.05 for the east and west deck to model the radiant barrier's high reflectance. The effect of the uncovered rafters on the deck emittance was neglected.

The physical length and width of the attic and the roof pitch were input to reflect the layout of the attic test module: 16 ft (4.9 m) long by 14 ft (4.3 m) wide with 22.6° roof pitch. The physical area of the inlet and outlet vents was a required input. Since the rate of ventilation was specified, the area was not used to estimate ventilation.

The duct system was modeled as 15 supply segments of various lengths to have the start of each segment correspond to the location of an average duct temperature or a centerline temperature measurement (see Figure 4). The inside diameter of the duct wall and the outside diameters of both the duct wall and the duct insulation corresponded to measured values. The thermal conductivity of the duct insulation was obtained from the R-value measured in a guarded hot plate for a sample of the duct insulation. The measured R-value of 5.74 h·ft²·°F/Btu (1.01 m²·K/W) for 1.625 in. (4.13 cm) thickness yielded thermal conductivity of 0.0236 Btu/h·ft·°F (0.0408 W/m·K). The infrared emittance of the outside surface of the duct insulation

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was estimated to be 0.05 for aluminum foil. Trials above and below this value showed worse agreement between corresponding measured and predicted duct air temperatures. The measured volumetric flow rate at standard conditions of 70°F (21°C), 1 atm, into and out of the duct system was converted to mass flow rate and assigned as input to each segment. Mass leakage is allowed by inputting lower mass flow rates into segments after leaky ones. The difference between mass flow rates for adjacent segments is the leakage from the upstream segment.

A node is assigned in ATICSIM to each of the various components of the attic and the segments of the duct system. Energy balances are achieved for each node at each hourly time step accounting for energy effects due to thermal conduction, convection, radiation, and moisture transport as appropriate to the node. The output from the model for this study was the set of temperatures for the east and west deck, for the north and south interior gable, the attic insulation surface, and the attic air, as well as the values for average duct air temperature in each of the 15 segments when a duct system was present. Since the measured thermal conductance of the ceiling insulation and the measured surface temperature on the bottom of the ceiling were input in our use of ATICSIM, accuracy of the predicted heat flux through the ceiling was not independent of that for predicted attic insulation surface temperature. Therefore, only the insulation surface temperature is reported.

RESULTS AND DISCUSSION

Steady-state conditions were imposed to study the effect of ventilation without and with a radiant barrier installed on the bottom of the roof deck. A summary of the conditions is listed in Tables 1a to 1d. No tests were done without ducts and without a radiant barrier at the winter condition. Extensive tests have been done in the past at nighttime or low solar gain winter conditions with the attic test module to learn the effect of a horizontal radiant barrier (Wilkes and Childs 1993). The mild winter condition with a warm roof sought the effects of a radiant barrier and varying attic ventilation rate on a sunny winter day because we suspected that the heating penalty would be more severe than observed for radiant barriers at cold nighttime or low solar gain conditions. The summer condition allows peak attic air temperatures above 125°F (52°C) observed in unvented attics on sunny summer days in the southern and southwestern U.S.

All measured values are averages over the steady-state portion of each test, at least four consecutive hours in accordance with ASTM C-236 procedures (ASTM 1989). Tables 1a to 1d show the distinct advantage of testing in climate simulators—the ability to reproduce conditions not being varied from test to test. The reproducibility of the climate chamber, metering chamber, and ceiling and rooftop temperatures as ventilation rate varied was ±0.1°F, ±0.1°F, ±0.1°F, and ±2°F (±0.06°C, ±0.06°C, ±0.06°C, and ±1°C), respectively. Rooftop temperatures in the winter tests without ducts were lower than the temperatures in the tests with ducts due to a mistake in manually setting the rooftop temperature setpoint without ducts.

Table 1 includes the R-values of the insulation and gypsum ceiling, termed $R_{ceiling}$ and measured in each test as the difference in temperatures from the top of the insulation to the bottom of the ceiling divided by the net heat flow per unit area into the open area of the metering chamber. The data in Table 1, supplemented by those for the work by Gu et al. (1996), yield average R-values of 13±1 h·ft²·°F/Btu (2.3±0.2 m²·K/W) at a mean temperature near 50°F (10°C) for the winter tests and 10.7±0.5 h·ft²·°F/Btu (1.9±0.1 m²·K/W) at a mean temperature near 95°F (35°C) for the summer tests. Most of the scatter about the mean values occurred from installation of the radiant barrier. A least-squares fit of R-values from tests before installation of the radiant barrier lies R_{US}-0.7 (R_{SI}-.12) above the average for the winter tests and R_{US}-0.4 (R_{SI}-0.07) above the average for the summer tests. A fit of R-values from tests after installation of the radiant barrier lies R_{US}-0.7 (R_{SI}-0.12) below the winter mean and R_{US}-0.4 (R_{SI}-0.07) below the summer mean.

The flow rates measured by the hot wire anemometers at the inlet and exit of the duct system were identical within an observed uncertainty of ±5 scfm (±0.15 m³/min at 21°C, 1 atm). The flow rates were higher than the 100 to 300 scfm (2.8 to 8.5 m³/min) recommended in 6-in. (15-cm) diameter round duct (ASHRAE 1993b) to avoid icing of the duct system air conditioner cooling coil during operation at the summer condition. The ventilation is reported two ways in Tables 1a to 1d. One is in terms of total ventilation flow rate divided by the ceiling area, which is 180 ft² (16.7 m²) for the attic test module. To convert from cfm/ft² to m³/min×m² multiply by 0.305. The other is in terms of air changes per hour for the 540 ft³ (15.3 m³) of attic volume. None, low and medium ventilation rates cover the range of ventilation rates per unit area given in the 1993 Handbook of Fundamentals (ASHRAE 1993c) for estimating the effective thermal resistance of ventilated attics. The low ventilation rate of 0.3 to 0.8 cfm/ft² (0.09 to 0.24 m/min) is already considerably greater than 0.1 cfm/ft² (0.03 m/min) assumed as the natural ventilation rate of attics in the 1993 HOF. The high ventilation rate, which was the maximum rate allowed by the soffit vent blowers, was included in the tests to show the maximum effect of power ventilation. The hot wire anemometers to measure ventilation flow rate to each soffit are from the same manufacturer as the ones for the duct air flow rate. The uncertainty for total ventilation flow rate is assumed to be what was observed for duct air flow rate, ±5 scfm (±0.15 m³/min at 21°C, 1 atm). Dampers to control the flow rate to each soffit vent were adjusted so that flow rates for each side were equal within this uncertainty.

The average of the ventilation air temperatures into the two soffit plenums is shown for cases where ventilation was non-zero. The ventilation air temperature was constant to about ±1°F (±0.6°C) and was significantly higher than the climate chamber temperature at winter conditions because the

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TABLE 1
Conditions in Tests for the Effects of Ventilation

Ventilation Level:	$T_{\text{climate chamber}}$ (°F)	$T_{\text{metering chamber}}$ (°F)	T_{ceiling} (°F)	$T_{\text{roof top}}$ (°F)	R_{ceiling} (h·ft·°F/Btu)	$Q_{\text{into duct}}$ (scfm)	$T_{\text{air into duct}}$ (°F)	Ventilation (cfm/ft/ACH)	$T_{\text{ventilation air}}$ (°F)
a. Mild winter condition with insulated ducts									
Without radiant barrier									
None	20.7	70.1	69.3	58.1	13.4	415	115.3	0 / 0	N.A.
Low	21.8	70.2	69.2	57.4	14.7	415	115.4	0.7 / 14	30.8
Medium	20.8	70.2	68.9	58.0	14.4	415	115.3	1.6 / 32	28.7
High	20.9	70.5	68.9	57.8	14.6	415	115.3	2.8 / 56	27.6
With radiant barrier									
None	20.7	70.2	69.1	57.3	11.8	404	115.2	0 / 0	N.A.
Low	20.8	70.3	68.9	57.1	12.7	404	115.4	0.8 / 17	29.0
Medium	20.8	70.3	68.6	58.0	12.2	404	115.3	1.6 / 32	28.5
High	21.0	70.5	68.6	57.5	12.4	404	115.3	2.8 / 57	27.9
b. Severe summer condition with insulated ducts									
Without radiant barrier									
None	110.8	70.1	72.4	149.6	10.9	440	59.7	0 / 0	N.A.
Low	110.8	70.2	72.3	149.2	11.1	440	59.6	0.6 / 13	112.8
Medium	110.8	70.2	72.3	149.6	10.9	440	59.7	1.4 / 27	112.8
High	110.9	70.3	72.1	148.8	11.3	440	59.6	2.3 / 45	113.2
With radiant barrier									
None	110.9	70.0	71.4	148.8	10.0	442	59.2	0 / 0	N.A.
Low	110.9	70.2	71.5	148.8	9.8	442	59.3	0.6 / 13	112.9
Medium	110.8	70.2	71.4	149.8	10.3	442	59.4	1.3 / 26	112.8
High	110.8	70.2	71.4	149.8	10.4	442	59.2	2.3 / 45	113.0
c. Mild winter condition without ducts									
With radiant barrier									
None	21.1	70.2	68.7	47.8	12.5	N.A.	N.A.	0 / 0	N.A.
Low	21.0	70.2	68.7	47.8	12.4	N.A.	N.A.	0.5 / 10	28.7
Medium	20.8	70.2	68.6	47.7	12.5	N.A.	N.A.	1.8 / 35	27.5

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TABLE 1 (Continued)
Conditions in Tests for the Effects of Ventilation

Ventilation Level:	$T_{climate\ chamber}$ (°F)	$T_{metering\ chamber}$ (°F)	$T_{ceiling}$ (°F)	$T_{rooftop}$ (°F)	$R_{ceiling}$ (h·ft·°F/Btu)	$Q_{into\ duct}$ (scfm)	$T_{air\ into\ duct}$ (°F)	Ventilation (cfm/ft/ACH)	$T_{ventilation\ air}$ (°F)
High	21.2	70.4	68.6	47.9	12.3	N.A.	N.A.	2.8 / 57	26.8
d. Severe summer condition without ducts									
Without radiant barrier									
None	111.0	70.0	73.2	148.8	10.1	N.A.	N.A.	0 / 0	N.A.
Low	111.0	70.0	73.2	149.0	9.9	N.A.	N.A.	0.4 / 7½	112.5
Medium	111.4	70.1	73.0	149.0	9.6	N.A.	N.A.	1.4 / 28	113.1
High	111.2	70.2	72.8	149.2	10.0	N.A.	N.A.	2.3 / 45	113.3
With radiant barrier									
None	111.0	70.0	72.3	148.8	11.1	N.A.	N.A.	0 / 0	N.A.
Low	111.7	70.0	72.3	148.8	11.0	N.A.	N.A.	0.3 / 6½	114.1
Medium	111.9	70.1	72.1	148.6	11.2	N.A.	N.A.	1.5 / 30	114.0
High	111.1	70.2	72.1	149.0	11.3	N.A.	N.A.	2.3 / 46	113.6

TABLE 2
Comparison of Test Results and ATICSIM Predictions for the Effects of Ventilation

Ventilation Level	$\Delta T_{duct\ air}$ (°F)		Diff.	Attic Air (°F)		Diff.	Attic Insul.(°F)		Diff.	Deck (°F)		Diff.	Gable (°F)		Diff.
	meas.	pred.	p - m	meas.	pred.	p - m	meas.	pred.	p - m	meas.	pred.	p - m	meas.	pred.	p - m
a. Mild winter condition with insulated ducts															
Without radiant barrier															
None	1.13	1.18	0.05	55.0	52.4	-2.6	53.6	44.2	-9.4	56.9	53.1	-3.8	43.6	39.0	-4.6
Low	1.30	1.46	0.16	50.9	37.5	-13.4	48.8	40.1	-8.7	54.2	49.6	-4.6	41.4	35.6	-5.8
Medium	1.44	1.55	0.11	43.0	32.6	-10.4	42.4	38.1	-4.3	50.9	48.5	-2.4	37.0	33.3	-3.7
High	1.57	1.61	0.04	38.0	30.1	-7.9	39.2	36.8	-2.4	48.6	47.6	-1.0	34.5	32.1	-2.4
With radiant barrier															
None	1.12	1.25	0.13	54.3	50.6	-3.7	50.5	37.1	-13.4	57.1	54.5	-2.6	42.8	35.9	-6.9
Low	1.21	1.57	0.36	47.7	34.4	-13.3	43.4	31.8	-11.6	54.3	50.9	-3.4	38.8	31.5	-7.3
Medium	1.40	1.63	0.23	40.4	31.6	-8.8	38.0	29.9	-8.1	51.3	50.7	-0.6	34.5	29.6	-4.9
High	1.46	1.67	0.21	36.0	29.8	-6.2	35.1	29.0	-6.1	48.0	49.8	1.8	32.1	28.8	-3.3
Difference: With-Without Radiant Barrier															

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TABLE 2 (Continued)
Comparison of Test Results and ATICSIM Predictions for the Effects of Ventilation

Ventilation Level	$\Delta T_{duct\ air}$ (°F)		Diff.	Attic Air (°F)		Diff.	Attic Insul.(°F)		Diff.	Deck (°F)		Diff.	Gable (°F)		Diff.
	meas.	pred.	p - m	meas.	pred.	p - m	meas.	pred.	p - m	meas.	pred.	p - m	meas.	pred.	p - m
None	*-0.01*	0.07		*-0.7*	*-1.8*		*-3.1*	*-7.1*		0.2	1.4		*-0.8*	*-3.1*	
Low	*-0.09*	0.11		-3.2	*-3.1*		*-5.4*	*-8.3*		0.1	1.3		*-2.6*	*-4.1*	
Medium	*-0.04*	0.08		-2.6	*-1.0*		*-4.4*	*-8.2*		0.4	2.2		*-2.5*	*-3.7*	
High	*-0.11*	0.06		*-2.0*	*-0.3*		*-4.1*	*-7.8*		*-0.6*	2.2		*-2.4*	*-3.3*	
b. Severe summer condition with insulated ducts															
Without radiant barrier															
None	1.20	1.22	0.02	126.5	128.2	1.7	122.4	128.1	5.7	135.9	138.3	2.4	122.1	123.6	1.5
Low	1.24	1.06	-0.18	123.3	120.1	-3.2	120.1	125.7	5.6	134.3	136.3	2.0	120.1	121.5	1.4
Medium	1.23	1.03	-0.20	120.2	117.1	-3.1	119.1	124.9	5.8	133.3	135.6	2.3	119.0	120.8	1.8
High	1.22	1.02	-0.20	118.6	115.9	-2.7	118.3	124.2	5.9	132.2	134.8	2.6	118.4	120.2	1.8
With radiant barrier															
None	0.90	1.16	0.26	113.9	126.3	12.4	101.0	116.6	15.6	134.8	141.0	6.2	110.5	116.2	5.7
Low	0.86	1.02	0.16	110.5	117.6	7.1	99.6	113.9	14.3	133.0	138.9	5.9	109.6	113.8	4.2
Medium	0.78	0.99	0.21	108.9	115.6	6.7	99.5	113.4	13.9	132.8	139.1	6.3	109.2	113.4	4.2
High	0.91	0.98	0.07	109.8	114.7	4.9	101.1	113.3	12.2	132.5	138.8	6.3	109.9	113.4	3.5
Difference: With-Without Radiant Barrier															
None	*-0.30*	*-0.06*		*-12.6*	*-1.9*		*-21.4*	*-11.5*		*-1.1*	2.7		*-11.6*	*-7.4*	
Low	*-0.38*	*-0.04*		*-12.8*	-2.5		*-20.5*	*-11.8*		*-1.3*	2.6		*-10.5*	*-7.7*	
Medium	*-0.45*	*-0.04*		*-11.3*	*-1.5*		*-19.6*	*-11.5*		*-0.5*	3.5		*-9.8*	*-7.4*	
High	*-0.31*	*-0.04*		*-8.8*	*-1.2*		*-17.2*	*-10.9*		0.3	4.0		*-8.5*	*-6.8*	
c. Mild winter condition without ducts				Attic Air (°F)		Diff.	Attic Insul.(°F)		Diff.	Deck (°F)		Diff.	Gable (°F)		Diff.
With radiant barrier	Ventilation Level			meas.	pred.	p - m	meas.	pred.	p - m	meas.	pred.	p - m	meas.	pred.	p - m
	None			34.7	42.8	8.1	34.4	44.1	9.7	43.0	47.0	4.0	30.1	31.4	1.3
	Low			33.7	34.4	0.7	33.1	38.0	4.9	42.4	45.1	2.7	29.4	28.4	-1.0
	Medium			32.0	29.6	-2.4	31.6	34.3	2.7	41.3	43.9	2.6	28.5	26.9	-1.6
	High			30.4	28.2	-2.2	31.1	33.2	2.1	40.0	43.7	3.7	28.0	26.2	-1.8
Difference: With-Without Ducts															

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TABLE 2 (Continued)
Comparison of Test Results and ATICSIM Predictions for the Effects of Ventilation

Ventilation Level	$\Delta T_{duct\ air}$ (°F)		Diff.	Attic Air (°F)		Diff.	Attic Insul.(°F)		Diff.	Deck (°F)		Diff.	Gable (°F)		Diff.
	meas.	pred.	p - m	meas.	pred.	p - m	meas.	pred.	p - m	meas.	pred.	p - m	meas.	pred.	p - m
		None		19.6	7.8		16.1	**-7.0**		14.1	7.5		12.7	4.5	
		Low		14.0	0.0		10.3	**-6.2**		11.9	5.8		9.4	3.1	
		Medium		8.4	2.0		6.4	**-4.4**		10.0	6.8		6.0	2.7	
		High		5.6	1.6		4.0	**-4.2**		8.0	6.1		4.1	2.6	
d. Severe summer condition without ducts															
Without radiant barrier															
		None		132.5	136.5	4.0	131.6	134.9	3.3	138.6	141.2	2.6	120.2	127.3	7.1
		Low		131.3	125.3	-6.0	130.2	130.3	0.1	137.8	138.2	0.4	119.7	124.5	4.8
		Medium		124.4	118.1	-6.3	124.6	126.2	1.6	134.1	135.7	1.6	118.3	122.3	4.0
		High		122.0	116.6	-5.4	123.1	125.5	2.4	133.6	135.2	1.6	117.3	121.6	4.3
Difference: With-Without Ducts															
		None		**-6.0**	**-8.3**		**-9.2**	**-6.8**		**-2.7**	**-2.9**		1.9	**-3.7**	
		Low		**-8.0**	**-5.2**		**-10.1**	**-4.6**		**-3.5**	**-1.9**		0.4	**-3.0**	
		Medium		**-4.2**	**-1.0**		**-5.5**	**-1.3**		**-0.8**	**-0.1**		0.7	**-1.5**	
		High		**-3.4**	**-0.7**		**-4.8**	**-1.3**		**-1.4**	**-0.4**		**1.1**	**-1.4**	
With radiant barrier															
		None		122.9	132.7	9.8	117.6	115.6	-2.0	137.9	144.6	6.7	117.4	117.4	0.0
		Low		121.6	123.9	2.3	116.5	112.3	-4.2	137.5	142.6	5.1	117.1	115.4	-1.7
		Medium		117.4	117.1	-0.3	114.3	110.1	-4.2	135.2	140.8	5.6	115.0	113.6	-1.4
		High		116.0	115.8	-0.2	113.7	109.7	-4.0	134.2	140.7	6.5	114.4	112.9	-1.5
Difference: With-Without Radiant Barrier															
		None		*-9.6*	*-3.8*		*-14.0*	*-19.3*		*-0.7*	3.4		*-2.8*	*-9.9*	
		Low		*-9.7*	*-1.4*		*-13.7*	*-18.0*		*-0.3*	4.4		*-2.6*	*-9.1*	
		Medium		*-7.0*	*-1.0*		*-10.3*	*-16.1*		1.1	5.1		*-3.3*	*-8.7*	
		High		*-6.0*	*-0.8*		*-9.4*	*-15.8*		0.6	5.5		*-2.9*	*-8.7*	
Difference: With-Without Ducts															
		None		**-9.0**	**-6.4**		**-16.6**	1.0		**-3.1**	**-3.6**		**-6.9**	**-1.2**	
		Low		**-11.1**	**-6.3**		**-16.9**	1.6		**-4.5**	**-3.7**		**-7.5**	**-1.6**	
		Medium		**-8.5**	**-1.5**		**-14.8**	3.3		**-2.4**	**-1.7**		**-5.8**	**-0.2**	
		High		**-6.2**	**-1.1**		**-12.6**	3.6		**-1.7**	**-1.9**		**-4.5**	0.5	

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infrared lights heated the dark-surfaced tubes carrying ventilation air to the plenums along the eaves of the test section. At winter conditions, this heating mechanism meant that the higher the ventilation rate, the lower the ventilation air temperature. At summer conditions, ventilation air temperature was only slightly warmer than the climate chamber air and ventilation rate had little effect on it.

Tables 2a through 2d present the duct air temperature changes and attic air, attic insulation, and deck and gable temperatures for each test. The predictions of the attic model for the same quantities are listed next to each measurement. Extra columns are inserted next to the pairs of measurements and predictions, giving the respective differences between the predictions and the measurements (p - m). Extra rows are inserted after data without and with the radiant barrier to give the differences due to the radiant barrier (in italics) between respective measurements and between respective predictions for otherwise comparable conditions. Similarly, extra rows are inserted after data without ducts to give the differences due to the duct system (in bold) between respective measurements and respective predictions for otherwise comparable conditions, ignoring the effect of the different rooftop temperatures in the winter tests with and without ducts.

The duct air measurements and predictions are presented as the temperature drop (winter conditions) or temperature rise (summer conditions) from the inlet to outlet of the duct system in the attic. The duct system was 31 ft (9.4 m) long including two 90° elbows. The temperatures indicated by the first and last arrays for average air temperature over the inside duct area were used to make the difference. The duct air temperature changes from inlet to outlet of the ducts are small for all cases because the duct run was short, insulated duct was used, and the flow rate of air in the ducts was high. The measured duct air temperature change shows a slight increase with ventilation rate at winter conditions as cold ventilation air swept over the insulated ducts. There is no apparent effect of ventilation rate on duct air temperature change at the summer conditions. This is likely due to stratification of cooler air at the level of the ducts in summer that the warm ventilation air did not penetrate.

The attic air temperatures in Tables 2a through 2d are averages over all five levels at which thermocouples were suspended between the ridge and the attic insulation along the ridge line (see Figure 3). Details about variations in attic air temperatures at the five levels are presented in Figure 5. The attic insulation temperatures are the averages from the thermocouples in the frame lowered to the insulation surface. Seven in the center of the frame were used with the duct system in place and seventeen in the entire frame were monitored without the ducts. The deck temperatures are averages from three measurements under the deck on each side of the roof. There was no significant variation about the respective average insulation and deck temperatures reported in Tables 2a through 2d. The gable temperatures are the averages from single thermocouples on the inside of each gable, and there was no significant variation about the averages. All measured temperatures inside the attic appear to consistently increase or decrease as ventilation rate increases except a few data in Table 2b at the severe summer condition with ducts and a radiant barrier in place. For these cases the medium and high power ventilation rates are about as effective as the low rate.

At the mild winter condition in Tables 2a and 2c, the attic air, attic insulation surface, and deck temperatures decrease regularly as ventilation rate increases. Circulation of more and more ventilation air that is cooler than the roof would be expected to further cool the attic. The same mechanism is at work for summer conditions without a radiant barrier, but the changes in temperature from none to high ventilation rate are less than for the winter condition and the scatter is larger. As noted above, the effect seems to be less than the scatter at the summer condition with ducts and the radiant barrier. With the ducts installed, summer attic air temperatures are slightly cooler than the ventilation air temperatures, mainly because the surface area of the insulated ducts, which carried cool air throughout the summer tests, was cooler than the ventilation air temperature. The chambers below the attic were kept at room temperature and also influenced attic temperatures through the attic insulation.

Attic ventilation affected the stratification of attic air temperatures, and Figure 5 shows the trends. At the winter condition with ducts but without a radiant barrier installed, air temperatures were 2°F (1.1°C) cooler near the attic insulation (33 in. or 84 cm down) and 1°F (0.6°C) warmer near the ridge than the reported averages for no, low, and medium ventilation. With ducts and a radiant barrier, the stratification was slightly more pronounced: 3°F (1.7°C) cooler near the insulation and 2°F (1.1°C) warmer near the ridge. Stratification nearly disappeared for the high ventilation rate and without ducts.

At the summer condition with ducts but without a radiant barrier installed, temperatures near the insulation went from 6°F (3.3°C) cooler to no cooler than the average as ventilation increased from none to high. Near the ridge they went from 4°F (2.2°C) warmer to no warmer. With ducts and a radiant barrier installed, stratification persisted despite the high rates of power ventilation. Temperatures near the insulation went from 13°F (7°C) cooler with no ventilation to 9°F (5°C) cooler with the high ventilation. Near the ridge the temperatures were from 9°F (5°C) warmer to 4°F (2.2°C) warmer. Without ducts, there was little stratification except at no and low ventilation rates with a radiant barrier.

The data for differences with and without the radiant barrier in Tables 2a, 2b, and 2d show that the radiant barrier had a significant effect on attic air and insulation temperatures. Because roof temperatures were controlled to a desired temperature from test to test, deck temperatures were not significantly affected by the presence of this radiant barrier. At the winter condition with the ducts installed, attic air temperatures are lower by 1°F to 3°F (0.6°C to 1.7°C) and attic insulation surface temperatures are lower by 3°F to 5°F (2°C to

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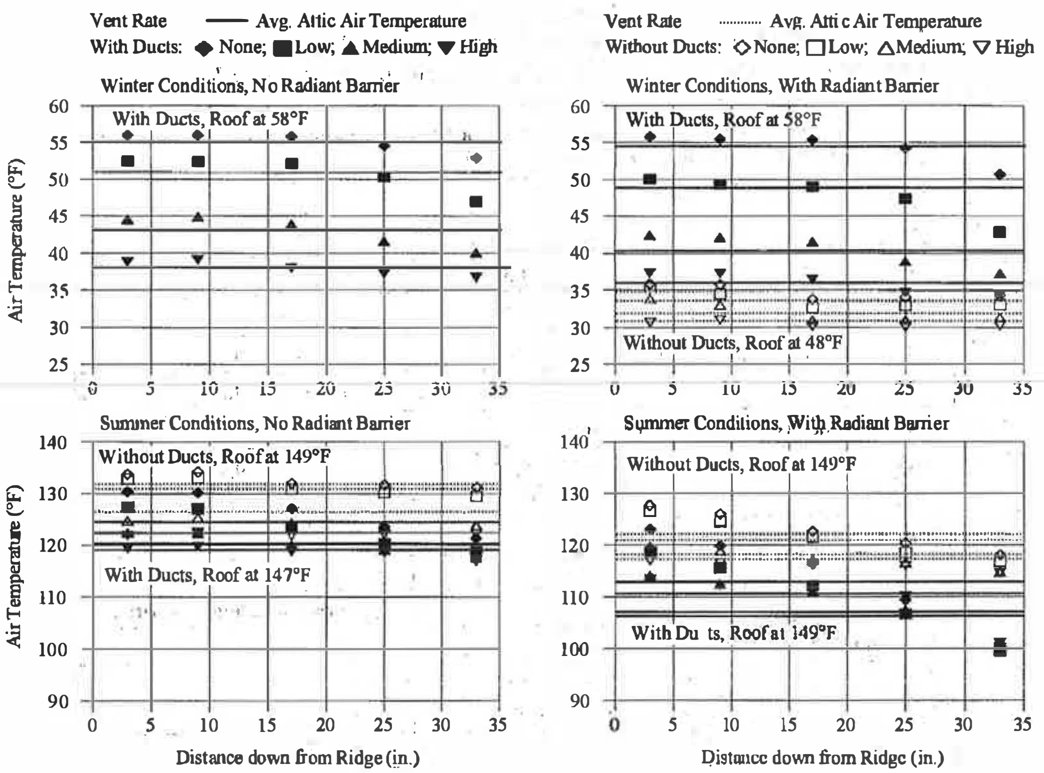

Figure 5 *Attic air temperature stratification vs. ventilation rate from thermocouple arrays down the center of the test module.*

3°C) due to the radiant barrier, independent of ventilation rate. At the summer condition with the ducts installed, attic air and insulation temperatures are a desirable 10°F to 13°F (5.6°C to 7.2°C) and 17°F to 21°F (9°C to 12°C) cooler, respectively, with the radiant barrier; the lower the attic ventilation rate, the more the benefit. At the summer condition without the ducts installed, attic air and insulation temperatures are affected slightly less by the radiant barrier, 6°F to 10°F (3.3°C to 5.6°C) and 9°F to 14°F (5°C to 8°C) cooler, respectively.

Table 3 combines the attic insulation temperatures from Table 2 with ceiling temperatures and R-values from Table 1 to show the effect of the radiant barrier on ceiling heat flux. The ceiling heat fluxes in Table 3 are computed from

$$q = \frac{T_{attic\ insulation} - T_{ceiling}}{R_{ceiling}} \qquad (1)$$

where

q = heat flux (+ downward through the ceiling),

$T_{attic\ insulation}$ = measured temperature at the surface of the insulation,

$T_{ceiling}$ = measured temperature at the bottom of the gypsum ceiling, and

$R_{ceiling}$ = R-value of the gypsum and insulation measured from an energy balance on the metering chamber below the attic test module.

Table 3 shows that the cooling benefits and heating penalty of this radiant barrier are generally lowest at the highest ventilation rate. They do not vary consistently with ventilation rate, most likely because of the variation in R-value from test to test.

At the severe summer condition, the cooling benefit averages 29% without ducts and is slightly higher, 34%, with ducts. Table 1 shows that the ceiling R-value varies from R_{US}-10 to 11 (R_{SI}-1.8 to 1.9) for the summer tests. For the truss radiant barrier studied by Levins and Karnitz (1987) with R_{US}-11 (R_{SI}-1.9) attic insulation, the cooling season average benefit was 11%. The values are not directly comparable, although the peak value on a severe summer day should be significantly greater than the seasonal average. Ober (1989) gives data more directly comparable to the cooling benefit data in Table 3. Weekly average peak heat fluxes for a house with R_{US}-19 (R_{SI}-3.3) ceiling insulation with and without radiant barrier foil draped over the rafters showed 34.4% reduction due to the radiant barrier. Levins and Karnitz (1987) report that the reduction in annual cooling energy for R_{US}-19 (R_{SI}-3.3) insulation and a horizontal radiant barrier and R_{US}-11 (R^{SI}-1.9) insulation and a horizontal radiant barrier, both relative to R_{US}-11 (R_{SI}-1.9) insulation and no radiant barrier, are 25% and 16%, respectively, a 9% difference. Subtracting 9% from

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TABLE 3
Cooling Benefit and Heating Penalty of the Radiant Barrier (RB) at the Severe Summer and Mild Winter Conditions of the Tests

Ventilation Level:	$q_{\text{with RB}}$ (Btu/h·ft·)	$q_{\text{without RB}}$ (Btu/h·ft·)	$(q_{\text{with RB}}-q_{\text{without RB}})/q_{\text{without RB}}$ (%)
Severe summer condition with ducts			
None	2.96	4.59	−35.5
Low	2.87	4.31	−33.4
Medium	2.73	4.29	−36.5
High	2.86	4.09	−30.2
			Average Cooling Benefit: 34%
Severe summer condition without ducts			
None	4.08	5.78	−29.4
Low	4.02	5.76	−30.2
Medium	3.77	5.38	−29.9
High	3.68	5.03	−26.8
			Average Cooling Benefit: 29%
Mild winter condition with ducts			
None	−1.58	−1.17	+34.5
Low	−2.01	−1.39	+44.7
Medium	−2.51	−1.84	+36.3
High	−2.70	−2.03	+32.8
			Average Heating Penalty: 37%

Ober's 34% value for R_{US}-19 (R_{SI}-3.3) to apply it to R_{US}-11 (R_{SI}-1.9) insulation levels yields an estimated 25% cooling benefit at peak times. Our 29% cooling benefit with R_{US}-11 (R_{SI}-1.9) insulation and a truss radiant barrier is reasonable relative to Ober's field-measured peak reduction.

At the mild winter condition, Table 3 shows a heating penalty of 37%. Levins and Karnitz (1988) found an insignificantly small heating penalty with a truss radiant barrier and R_{US}-11 (R_{SI}-1.9) attic insulation. It is reasonable that the penalty be significant when the radiant barrier prevents mild sunny winter conditions from heating the attic, but no direct comparisons to data in the literature were found.

The duct system in our tests occupied a significant fraction of the small attic of the residential attic test module. Projected or plan area of the insulated ducts was 13% of the test module's ceiling area. Hence, even though insulated, the duct system noticeably affected conditions in the attic. With the radiant barrier at winter conditions, as attic ventilation rate decreased from high to none, attic air was 6°F to 20°F (3°C to 11°C) warmer and insulation surface temperatures 4°F to 16°F (2°C to 9°C) warmer with the duct system than without it. With the radiant barrier at summer conditions, attic air was 6°F to 10°F (3°C to 6°C) cooler and attic insulation surface temperatures 13°F to 17°F (7°C to 9°C) cooler with the ducts than without, the maximum effect occurring at the low attic ventilation rate but not by much compared to no ventilation. Without the radiant barrier at summer conditions, the effect on attic air and insulation surface temperatures was 3°F to 8°F (2°C to 4°C) and 5°F to 10°F (3°C to 6°C), respectively. The effect of the ducts on attic insulation temperature at the summer condition with the radiant barrier is particularly large and reflects the strong stratification of attic air temperatures at this condition due in part, we believe, to the way the duct system was installed parallel to and near the eaves of the test module.

Tables 2a to 2d also present the temperatures predicted by ATICSIM corresponding to all the measurements. Duct air temperature change is predicted within ±0.3°F (±0.2°C) over all the tests in which ducts were installed. Tables 4a through 4d display the average differences between the ATICSIM predictions and the measurements. The averages for all four cases are over the range of ventilation rates. Averages include differences with and without the radiant barrier except for the winter condition without ducts. Differences between predicted and measured duct air temperature change averaged +0.16°F (0.09°C) at the mild winter condition and +0.02°F (+0.01°C) at the severe summer condition, relative to a total change from 0.9°F to 1.5°F (0.5°C to 0.8°C). The tendency is to overpredict the duct air temperature change, especially at the mild winter condition.

Figure 6 shows a detailed comparison of test results and ATICSIM predictions for the effect of ventilation on air

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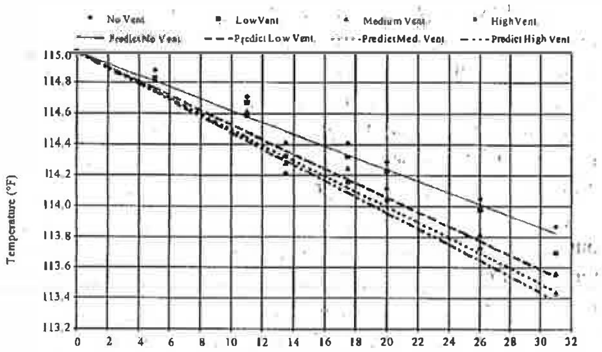

Figure 6 *Comparison of test results and ATICSIM predictions for the effects of ventilation on average temperatures along the insulated duct, example for winter conditions without a radiant barrier.*

temperatures along the duct, not just the difference between inlet and outlet temperatures in Tables 2a through 2d. The less accurate case in Table 4, the winter condition without a radiant barrier, is chosen as an example. To show trends more clearly, data were adjusted to have a common temperature of 115°F (46°C) into the duct for all ventilation rates. The measurements and predictions both show a linear decrease with distance down the duct for each ventilation rate, except for the measurements just after the first elbow (before 14 ft or 4.3 m along the duct) where the thermocouples are in a disturbed flow region.

Figure 6 shows steeper slopes as ventilation rate increases for the duct air temperature vs. distance down the duct for both measurements and predictions, which is consistent with decreasing attic air temperature around the ducts. The measurements show about the same change in slope for each approximately equal increment of ventilation rate, whereas the predictions show a relatively larger change of slope from no to low ventilation rate and less change from low to medium ventilation rate and from medium to high ventilation rate. The predictions show a diminishing effect of more and more ventilation and the experiments do not. ATICSIM assigns a single temperature to all of the air in the attic, which does not account for the changes in stratification of attic air temperatures with ventilation rate seen in Figure 5 even at winter conditions with a heated roof. This is not necessarily a shortcoming for use of ATICSIM as a design tool. Stratification was exacerbated by the way the ducts ran along the eaves in the test module. Such a situation would not likely occur in actual attics if the ducts run from a central plenum to diffusers in the ceilings of rooms under the attic or to connections with ducts in the exterior walls.

Regarding the ATICSIM predictions for attic air, attic insulation, and deck and gable temperatures in Tables 2a to 2d, the range of differences between the predictions and measurements are +2°F to −13°F (+1°C to −7°C) at the winter condition with insulated ducts. Without ducts, the predictions range within +10°F to −2°F (+6°C to −1°C). At the mild winter condition, accuracy varies randomly with ventilation rate and the radiant barrier seems to have no effect on the accuracy.

At the severe summer condition, with heat flow conditions reversed relative to the winter condition, the trends for ATICSIM's accuracy also reverse. With insulated ducts, the predictions range from +16°F to −3°F (+9°C to −2°C) relative to the measurements in Table 2b. The largest overpredictions are with the radiant barrier, which could be due to the way the radiant barrier was modeled in ATICSIM. Each half of the deck was assigned a single handbook value of reflectance, whereas only the exposed deck between rafters was covered by aluminum foil in the attic test module. No trials were done to vary the reflectance.

The difference between each prediction and its corresponding measurement for insulated ducts at the summer condition is almost constant as ventilation rate increases. ATICSIM predicts the trend with ventilation rate better at summer conditions than at winter conditions. Ventilation introduced relatively cooler air at summer conditions, so its

TABLE 4
Average Differences Between ATICSIM Predictions (P) and Measurements (M)
[For differences in °C, multiply by 0.56]

$\Delta T_{ductair}$	Attic Air	Attic Insulation	Deck	Gable
Avg. p - m (°F)	**Avg. p - m (°F)**	**Avg. p - m (°F)**	**Avg. p - m (°F)**	**Avg. p - m (°F)**
a. Mild winter condition with insulated ducts				
+0.16	-8.3	-8.0	+2.1	-4.9
b. Severe summer condition with insulated ducts				
+0.02	+3.0	+9.9	+4.3	+3.0
c. Mild winter condition without ducts				
N.A.	+1.1	+4.9	+3.3	-0.8
d. Severe summer condition without ducts				
N.A.	-0.3	-0.9	+3.8	+2.0

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effect was more dominant than at winter conditions. Note that the power ventilation used in the LSCS was modeled by a specific ventilation airflow rate in ATICSIM. In real attics with buoyancy-induced natural ventilation, ATICSIM's predictions would be subject to greater uncertainties associated with choosing appropriate densities to model the buoyancy forces.

Without ducts at the severe summer condition, the predicted temperatures inside the attic range within +10°F to −6°F (+6°C to −3°C). The agreement between predictions and measurements without ducts is better than with them, which can be attributed to the significant effect of the duct system used in the attic test module and the complicated effect its layout along the edges of the module had on attic performance. ATICSIM assigns a single node to each of the components of the attic and duct system so can capture limited spatial variations. Agreement within ±5°F (±3°C) between measurements and predictions was found using ATICSIM with and without horizontal radiant barriers in a duct free attic module at winter conditions (Wilkes and Childs 1993).

In Tables 4a and 4c, focusing on the attic air and insulation temperatures, the summary of average differences for the mild winter condition clearly shows significant underprediction with the ducts installed and slight overprediction without the ducts. The summary for the severe summer condition without ducts in Table 4d emphasizes that ATICSIM is very accurate for this case. On average, attic air and insulation temperatures are predicted within −0.9°F (−0.5°C). Comparing averages in Tables 4c and 4d from the mild winter condition to the severe summer condition, ATICSIM handles temperature effects very well without ducts installed. Tables 4a and 4b show that the effect of the temperature change from winter to summer conditions is not handled as well with the ducts installed, especially for the critical attic insulation temperature. However, the average accuracy exhibited for all of Table 4, ±10°F (±5.6°C), is considered adequate for design purposes. If fixed climatic conditions are used to explore effects of changes in duct system and attic details, the accuracy expected would improve to the entries in the relevant part of Table 4.

The detailed differences due to the radiant barrier and due to the ducts are also shown in Tables 2a through 2d for the ATICSIM predictions. They are very sensitive to the accuracy of ATICSIM. Trends of ATICSIM for the differences with and without the radiant barrier are generally the same as trends of the measurements as ventilation rate increases from none to high. Relative to the measurements, ATICSIM predicts essentially the same effect of the radiant barrier on attic air and insulation surface temperatures at the mild winter condition with the insulated ducts. The average heating penalty, reported in Table 3 as +37% from the measurements, is 47% using the predicted attic insulation temperatures. This illustrates the general principle that caution must be exercised when comparing data generated by taking differences.

Relative to the measurements, ATICSIM predicts less effect of the radiant barrier on attic air and insulation surface temperatures at the summer condition with the insulated ducts. This is a consequence of the overprediction of these temperatures with the radiant barrier. The average cooling benefit of the radiant barrier, which the measurements show is 34% in Table 3 at the severe summer condition with ducts, decreases to 12% using the predictions. At the summer condition without the ducts, the effect of the radiant barrier on the attic air temperature is again less relative to the measurements. However, ATICSIM predicts more effect on the attic insulation surface temperature because these temperatures are underpredicted with the radiant barrier. As a consequence, the predicted average cooling benefit of the radiant barrier without ducts increases to 37%, rather than the decrease shown by the measured 29%.

The effect of the ducts predicted by ATICSIM is less than exhibited by the measurements at the winter condition with the radiant barrier, especially for the attic insulation temperatures. This is the test situation in which roof temperatures were almost 10°F (6°C) cooler without the ducts. A run was made of ATICSIM without ducts but using roof temperatures from the simulation with ducts. Deck temperatures were about 7°F to 9°F (4°C to 5°C) warmer as ventilation rate decreased from high to none. Attic air temperatures increased 1°F to 6°F (0.6°C to 3°C) and attic insulation temperatures 1°F to 4°F (0.6°C to 2°C). This makes the duct effect predicted by ATICSIM even smaller. Of course, the measurements would have had similar changes if the roof temperature had been higher.

By underpredicting winter attic insulation surface temperatures with a radiant barrier and ducts and overpredicting them without ducts, ATICSIM predicts the opposite sign relative to the measurements for the effect of ducts on mild winter attic insulation temperatures. The same thing occurs at the severe summer condition with the radiant barrier. However, without the radiant barrier at summer conditions, the effect of the ducts predicted by ATICSIM agrees fairly well with the measurements.

Assigning a single node to each component of the attic in ATICSIM averages the effects of all the energy exchanged by the components into a single temperature for each. The attic air and insulation surface were not at a uniform temperature in the experiments. Figure 5 showed the stratification of attic air temperatures along the center of the attic test module, causing as much as a 20°F (11°C) difference in air temperatures from the bottom to the top of the attic. The measured insulation surface temperatures are reported in Tables 2a and 2b for the center of the metered area in Figure 4, away from the ducts. The thermocouples on the insulation surface under the ducts are close to the warm deck and seem to be affected more by the deck than the duct surface. Differences relative to temperatures at the center of the module are not as large as those in attic air due to stratification, but they are significant. With the radiant barrier, winter and summer, data not used for Table 2 show that the insulation under the duct was 2°F (1°C) warmer than

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Table 2 shows for the center of the metered area. Without the radiant barrier, the difference was 3°F to 4°F (1.5°C to 2°C). However, with large attics and ducts radiating out from a central plenum, the single-node approximation for each attic component should be better than it is for the small attic test module with large spatial variations due to placement of the ducts along the eave edges.

CONCLUSIONS

A simple duct system was installed in an attic test module for a large-scale climate simulator. The steady-state tests at a mild winter condition and a severe summer condition achieved careful control and reproducibility of conditions. This allowed us to document the effects of radiant barriers and a wide range of attic ventilation rates on the thermal performance of residential attics and attic duct systems. At both the summer and winter conditions, the roof surface was heated above ambient air temperatures by infrared lights, so, even at winter conditions, increasing attic ventilation rate decreased attic air and insulation surface temperatures.

At the mild winter condition, compared to measurements with no radiant barrier attached to the underside of the deck but the ducts installed, there was an average 37% increase in heat loss into the attic with the radiant barrier and ducts in place. This heating penalty varied randomly with ventilation rate in these tests. At the severe summer condition simulated in the tests, the radiant barrier decreased the heat gain through the ceiling. The average cooling benefit was 34% with ducts in the attic and 29% without them. Variation with ventilation rate was again random but there was less variation than at the mild winter condition.

Warm air in the insulated ducts at the mild winter condition warmed the attic air by 20°F (11°C) without ventilation. The maximum power ventilation rate of nearly 60 ACH diminished the effect to 6°F (3°C). Cool air in the ducts at the summer condition not only cooled the attic air by as much as 10°F (6°C) but also exacerbated stratification of air temperatures in the attic, which increasing ventilation rate did not appear to disturb. Placement of the ducts along the eaves in the residential attic test module for these tests is thought to have contributed to the stratification more than the placement of ducts in real attics would.

The computer program ATICSIM was used to predict the same temperatures as were measured inside the attic. Differences between predicted and measured duct air temperature change averaged +0.16°F (0.09°C) at the mild winter condition and +0.02°F (+0.01°C) at the severe summer condition, relative to a total change from 0.9°F to 1.5°F (0.5°C to 0.8°C). ATICSIM proved very accurate for attic air and insulation temperatures at the summer condition without ducts, predicting these temperatures on average within −1°F (−0.6°C). At the mild winter condition without ducts, attic air and insulation temperatures were predicted, on average, within +5°F (+2.8°C). With insulated ducts in the attic at summer conditions, the attic air and insulation temperatures were overpredicted by up to 10°F (6°C). The trends for accuracy with ducts in place at the winter condition were the opposite, with an average 8°F (4°C) underprediction. Based on the comparisons with the results of the tests at a mild winter condition and a severe summer condition, ATICSIM predictions for attic air and insulation temperatures should be accurate within ±10°F (±6°C). For design purposes, such as exploring the effect of changes in attic or duct system parameters, this should be adequate. If fixed climatic conditions are used, especially without ducts, accuracy may be better.

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