Thermal Performance of Fiberglass and Cellulose Attic Insulations

K.E. Wilkes, Ph.D., P.E.
Member ASHRAE

P.W. Childs

ABSTRACT

A series of experiments has been completed on the thermal performance of fiberglass and cellulose attic insulations under winter conditions using an attic test module in a guarded hot box facility. Experiments with one type of loose-fill fiberglass insulation showed that the thermal resistance at large temperature differences (70°F to 76°F) was about 35% to 50% less than at small temperature differences. The additional heat flow, attributed to natural convection, was effectively eliminated by applying a covering of fiberglass batts or a combination of a polyethylene film and fiberglass blankets. No significant convection was found either with fiberglass batts or with one type of loose-fill cellulose.

Using the experimental data along with an attic model, the additional energy costs due to convection in the coldest climate investigated were estimated to be $0.024/ft^2·yr to $0.029/ft^2·yr at the R-19 level and $0.014/ft^2·yr at the R-38 level. For the same conditions, annual energy savings due to upgrading insulation from the R-19 to the R-38 level were estimated to be $0.046/ft^2·yr to $0.070/ft^2·yr.

INTRODUCTION

Heat transfer through building insulations such as fiberglass and cellulose is usually considered to be a combination of conduction through still air, conduction through solid particles, and radiative transfer through a scattering, emitting, and absorbing medium. For applications in the U.S., heat transfer by natural convection has usually been considered to be negligible. Experiments performed by Wilkes and Rucker (1983), using an attic test module, showed that convection was negligible for batt insulation but was an important heat transfer mechanism under cold winter conditions (i.e., large temperature differences across the insulation) for a type of loose-fill fiberglass insulation. The influence of natural convection on heat flow through loose-fill insulation has also been observed by Besant and Miller (1983), Langlais et al. (1990), and Rose and McCaa (1991). Recent experiments on one type of loose-fill fiberglass insulation in a different attic test module and facility have been reported by Wilkes et al. (1991a, 1991b, 1992). At the largest temperature differences employed, the thermal resistance between the bottom of the gypsum board and the top of the insulation was 35% to 50% lower than at small temperature differences. In these experiments, the effectiveness of various covering materials in reducing convection was explored. The best of these covering systems appeared to nearly eliminate heat transfer by convection over the temperature range investigated.

Experiments with this attic test module have been continued, and additional data have been obtained with the attic insulated with loose-fill fiberglass, fiberglass batts, and loose-fill cellulose. This paper provides these additional data together with an analysis of these and previous results that illustrates the impact of convection on annual heating loads for a broad range of climatic conditions.

EXPERIMENTAL FACILITY

Large-Scale Climate Simulator

Experiments were performed using an attic test module in the Large Scale Climate Simulator (LSCS) at the DOE Roof Research Center (Huntley 1989), shown schematically in Figure 1. The attic test module separated the upper climate chamber from the lower metering and guard chambers. The walls of the metering chamber are insulated with four-inch-thick polyisocyanurate foam to minimize heat losses through the chamber walls. Although the metering chamber contains both heating and cooling equipment, all data reported here were obtained with the cooling equipment turned off. The temperatures in the metering and guard chambers were both controlled at a constant level of 70°F, while the temperature in the climate chamber was controlled at various steady levels between 45°F and -18°F.

Attic Test Module

The attic test module, shown schematically in Figure 2, was built to simulate a typical gabled attic residential construction and was 14 ft by 16 ft. It was constructed with nominal 2-by-4-inch wood joists and rafters, 24 inches on centers, with a 5 in 12 slope roof made of 0.5-inch-thick plywood covered with roofing felt and medium gray asphalt shingles. The ceiling consisted of 0.5-inch-thick gypsum board and the gables of 0.5-inch-thick plywood.

The attic was ventilated by a blower, with air entering through soffit vents and exiting through a ridge vent. The ventilation rate was measured using hot-wire anemometers in ducts leading to the soffit vents. Cardboard baffles were attached to the rafters near the eaves to prevent insulation from blocking the soffit vents and to prevent ventilation air

Kenneth E. Wilkes is a research staff member and Phillip W. Childs is a research technician at Oak Ridge National Laboratory, Oak Ridge, TN.

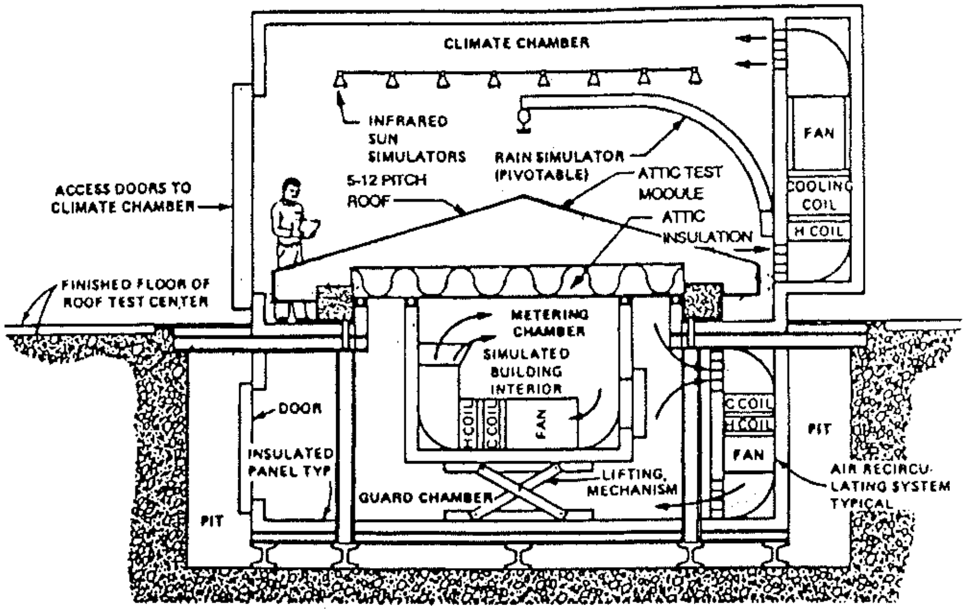

Figure 1 *Cross section of the large-scale climate simulator. The climate chamber at the top simulated outdoor conditions, and the metering chamber and guard chamber at the bottom simulated indoor conditions.*

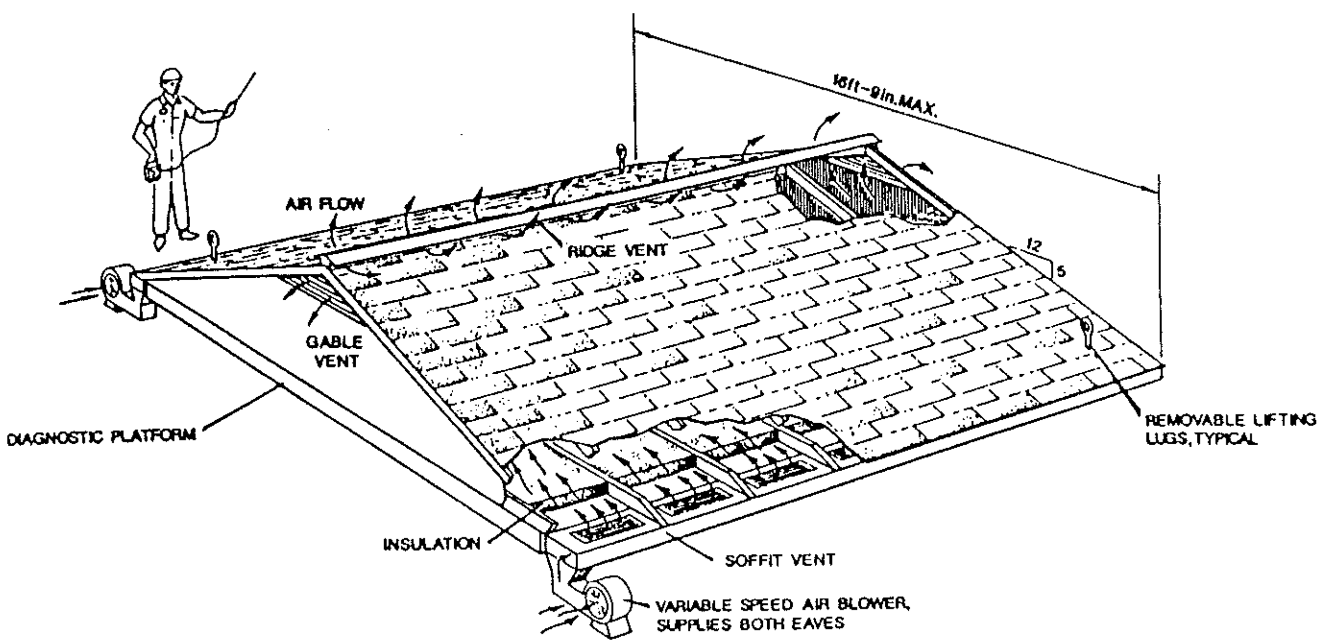

Figure 2 *Schematic of the attic test module.*

from blowing directly through the insulation. For most of the tests, a ventilation rate of about 0.1 cfm per square foot of attic floor was used.

Temperature-measuring instrumentation consisted of 125 thermocouples. Primary instrumentation was four arrays of 21 thermocouples each, arranged midway between the joists to measure temperatures in the metering chamber air, at the bottom surface of the gypsum board, at the top surface of the insulation, and in the attic air 3 inches above the insulation. Additional arrays of four thermocouples were placed in line with the joists on the top of the insulation and on the bottom of the gypsum board. Average temperatures for the top of the insulation and the bottom of the gypsum board were obtained by area weighting the readings of the thermocouples midway between the joists and over the joists. Thermocouples for the top of the insulation and for the attic air were mounted in an adjustable frame that was lowered until the bottom array of thermocouples was in contact with the insulation. Other thermocouples were located under the shingles, on the underside of the roof deck, on the inside and outside surfaces of the gables, in the attic air space, at the vent inlets and outlet, and on the top side of the gypsum board. All thermocouples were made from special limits-of-error copper-constantan wire, and all thermocouples for the bottom of the gypsum board and the top of the insulation were taken from the same spool of wire.

Data Reduction

Tests were run for about 24 hours, and the most stable 8-hour period near the end of the test was selected for use in the data analysis. Data consisting of the average heat flow through the ceiling, as calculated from a heat balance on the metering chamber, and all temperatures averaged over the array for a particular surface were collected every four minutes. Using quantities averaged over the eight-hour period, the surface-to-surface thermal resistance, R_{ss}, was calculated from the relationship

$$R_{ss} = \frac{A(T_b - T_t)}{Q} \qquad (1)$$

where A is the effective area of the ceiling exposed to the metering chamber (measured to the centerlines of the metering chamber walls, or 69.4 square feet), T_b is the temperature of the bottom of the gypsum board, T_t is the temperature at the top of the insulation, and Q is the heat flow. In conformance with normal reporting procedures for guarded hot box tests on nonhomogeneous building assemblies, the resistance defined in Equation 1 includes resistances due to the gypsum board and the wood joists as well as that due to the insulation materials.

Accuracy of Results

The accuracy of the thermal resistance measurements has been assessed by measurements on a 4-inch-thick panel made of expanded polystyrene foam for which the thermal conductivity has been independently determined using an unguarded thin-heater apparatus (Graves 1988) and also by measurements with the attic test module insulated with 5 inches of foam from the same lot of material. Results of these measurements are reported in Wilkes et al. (1992). A statistical analysis of thermal resistances measured in 37 tests with the 4-inch panel under simulated winter conditions, with the metering chamber's chilled water turned off, yielded 95% reproducibility intervals of ±1.9% to ±2.2% (depending upon the temperature level) and a bias of −3.3% to -4.3% (again depending upon the temperature level). A similar analysis for six tests with 5 inches of foam in the attic gave 95% reproducibility intervals of ±2.0% to ±2.6% and a bias of +2.5% to -0.4%.

MATERIALS TESTED

Data were obtained with the attic test module insulated with loose-fill fiberglass insulation, fiberglass batt insulation, and loose-fill cellulose insulation. Four specimens of loose-fill fiberglass insulation were obtained from two lots of the same type of material, with the second lot being produced at the same plant about nine months after the first one. Specimens 1 and 2 (denoted as LF-1 and LF-2) were taken from the first lot, and Specimens 3 and 4 (LF-3 and LF-4) were taken from the second lot. The elapsed times between production and installation of Specimens 1 through 4 were two days, six months, about one month, and about 2½ months, respectively. All four specimens were installed by a local insulation contractor, using a single blowing machine.

The target insulation R-value was R-19 for Specimens 1-3 and R-38 for Specimen 4. For the R-19 level, the label specifies a minimum thickness of 8¼ inches and a minimum material weight of 0.343 lb/ft^2. The minimum specifications for the R-38 level are 16 inches and 0.705 lb/ft^2. Actual characteristics of the specimens as installed are given in Table 1. Thicknesses and square foot weights for Specimens 1, 3, and 4 exceeded the target minima, as did the thickness of Specimen 2; however, the square foot weight of Specimen 2 fell short of the minimum by about 7%. Table 1 also gives estimated nominal insulation R-values obtained from extrapolations and interpolations of thermal conductivity-density data measured by ASTM C 518 (ASTM 1990). While the actual installed nominal insulation R-values depart somewhat from the target values, the specimens are referred to by their target values in this paper as a matter of convenience.

Unfaced R-19 fiberglass batt insulation was tested both alone and as a covering on loose-fill fiberglass Specimen 3. The batts tested alone had nominal dimensions of 6¼ inches by 24 inches by 48 inches. Three batts were placed in each joist cavity with their ends butted together and with the insulation covering the joists. The batts used as a covering on loose-fill Specimen 3 had nominal dimensions of 6¼ inches by 23¼ inches by 93 inches and were laid on top of

TABLE 1
Characteristics of Loose-Fill Fiberglass Specimens

Specimen	Average Thickness, in.	Average Density, lb/ft^3	Average Material Weight, lb/ft^2	Estimated Insulation R-Value at 75°F, h·ft^2·°F/Btu
Spec. 1 (LF-1)	9.5	0.48	0.38	21±1*
Spec. 2 (LF-2)	9.5	0.40	0.32	19±2*
Spec. 3 (LF-3)	9.5	0.45	0.36	20±1*
Spec. 4 (LF-4)	18	0.56	0.84	42±2*

* Estimated by extrapolation of thermal conductivity-density curves measured by ASTM C 518. Uncertainties represent 95% confidence intervals.

TABLE 2
Characteristics of Fiberglass Batt Insulation

Batt Dimensions	Average Thickness, in.	Average Density, lb/ft^3	Insulation R-Value at 75°F, h·ft^2·°F/Btu
6-1/4" X 24" X 48"	6.9	0.46	19.1*
6-1/4" X 23-1/4" X 93"	6.0	0.48	19.7**

* Measured at 6.25 in. thick, using ASTM C 518; average of three samples.

** Measured at 6.0 in. thick, using ASTM C 518; average of three samples.

the loose-fill with the batts perpendicular to the joists. Full-length batts were placed in the central 8-foot-square metering area, and shorter pieces were placed at each end. All batts were tightly butted against each other, both along the sides and at the ends. Average thicknesses and densities of the batts are given in Table 2, along with the nominal insulation R-values obtained from C 518 measurements.

A different fiberglass insulation product was used as a covering on loose-fill fiberglass Specimen 2. The covering system consisted of an 0.002-inch-thick unperforated white polyethylene film covered with one-inch-thick fiberglass blankets having a density of 1 lb/ft^3 and a nominal R-value of about 3.6 h·ft^2·°F/Btu (as measured by ASTM C 518).

Finally, one loose-fill cellulose insulation was tested. The target was an R-19 for which the label settled thickness is 5.13 inches and the label settled density is 2.00 lb/ft^3. Insulation was blown into the attic test module to a thickness of about 5.8 inches at a density of 1.9 lb/ft^3. After a few tests had been run with the insulation in the "as blown" condition, the bottom of the gypsum board was struck repeatedly with a block of wood in an effort to accelerate settling of the insulation, and another set of tests was run in the "settled" condition. The final thickness was 5.3 inches and the final density was 2.1 lb/ft^3. In this paper, the term "settled" is used to indicate the condition that was achieved in the test apparatus by an admittedly nonstandard settling procedure. This may or may not be a true representation of in-service settling. It should be noted that the thickness in both the "as blown" and the "settled" conditions was larger than the target label value for R-19 and that the average densities for these two conditions bracketed the label settled density. Based on ASTM C 518 measurements on this material, estimated nominal insulation R-values for the "as blown" and "settled" conditions are 21 and 19 h·ft^2·°F/Btu, respectively.

EXPERIMENTAL RESULTS AND DISCUSSION

The results of attic tests on each type of insulation are given in Table 3 and Figure 3. Table 3 lists the temperatures at the bottom of the gypsum board and the top of the insulation system and the surface-to-surface thermal resistance. Figure 3 shows the thermal resistance versus the difference of these two temperatures.

Loose-Fill Fiberglass Insulation Only

At temperature differences of 20°F to 30°F, the thermal resistances of LF-2, LF-3, and LF-4 were all close to the nominal values listed in Table 1. At larger temperature differences, the thermal resistance decreased until, at the largest temperature differences of 72°F to 76°F, the resistances were on the order of 35% to 50% lower. At

TABLE 3
Surface-to-Surface Thermal Resistances for Ceilings Insulated with Fiberglass or Cellulose

LF-1, R-19			LF-2, R-19			LF-3, R-19			LF-4, R-38			LF-2+Blankets,R-23		
T_b	T_t	R_{ss}	T_b	T_t	R_{ss}	T_b	T_t	R_{ss}	T_b	T_t	R_{ss}	T_b	T_t	R_{ss}
67.7	16.8	11.9	68.9	48.1	16.9	69.0	47.9	19.4	70.0	47.8	37.7	69.1	48.1	22.6
66.8	6.1	10.6	68.8	36.2	17.6	68.8	36.2	19.3	69.5	41.7	39.3	68.9	35.8	23.9
65.8	-4.0	9.1	68.3	25.8	16.3	68.9	36.1	19.3	69.2	35.4	40.5	68.7	25.0	24.1
			67.6	16.0	14.3	68.3	26.1	17.2	68.9	25.5	35.3	68.4	14.2	24.6
			67.6	15.1	14.3*	67.7	15.2	13.9	68.7	15.3	28.9	68.3	2.3	24.6
			67.0	5.3	12.1	66.9	4.1	12.2	68.4	3.5	23.9	68.0	-9.7	24.3
			66.2	-5.8	11.0	65.9	-6.2	10.5	67.9	-8.0	21.0			

LF-3+R-19 Batts,R-38			R-19 Batts			R-19 Cell., As-Blown			R-19 Cell., "Settled"		
T_b	T_t	R_{ss}	T_b	T_t	R_{ss}	T_b	T_t	R_{ss}	T_b	T_t	R_{ss}
69.3	34.4	38.8	68.9	47.9	19.4	68.6	43.4	20.1	68.6	44.1	18.1
69.1	12.4	40.9	68.7	36.8	19.8	68.2	14.1	20.8*	68.4	26.5	18.8
68.8	0.4	41.3	68.5	26.2	20.0	67.8	-7.6	21.8	68.1	15.5	19.5
68.7	-11.3	41.7	68.3	16.4	20.4				67.9	5.8	19.7
			68.1	6.0	20.4				67.7	-3.6	20.4
			67.8	-6.0	20.4						

Note: T_b = temperature of bottom of gypsum board, °F
T_t = temperature of top of insulation system, °F
R_{ss} = thermal resistance between bottom of gypsum board and top of insulation system, h·ft²·°F/Btu.
LF-1, LF-2, LF-3, LF-4 = loose-fill fiberglass Specimens 1, 2, 3, 4.
* indicates tests performed with no ventilation of attic.

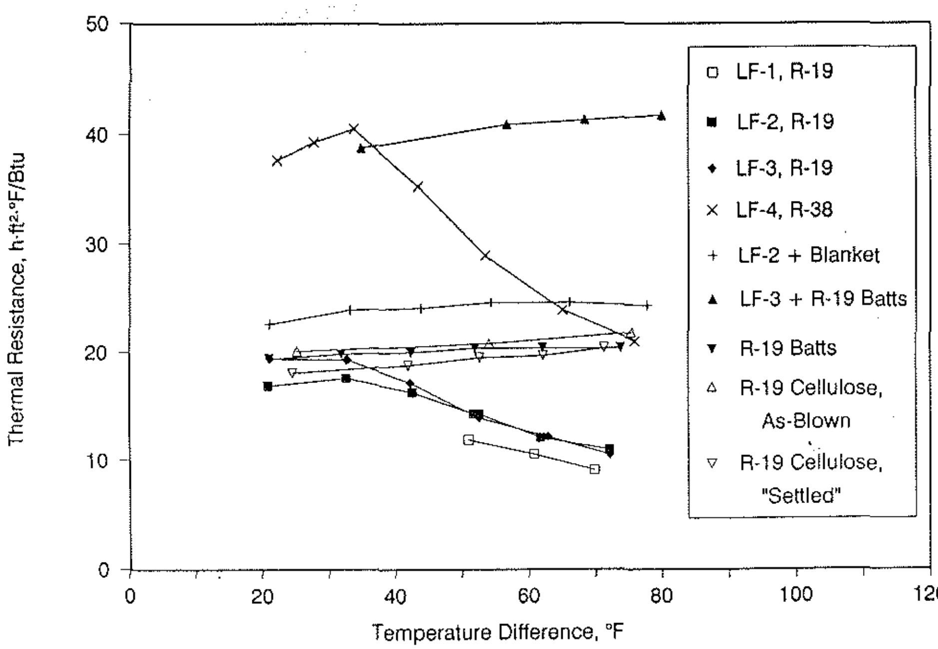

Figure 3 *Thermal resistance of ceilings insulated with fiberglass or cellulose attic insulations. The ordinate is the surface-to-surface thermal resistance between the bottom of the gypsum board and the top of the insulation system, and the abscissa is the temperature difference between these two locations. The indoor temperature was maintained near 70°F for all tests.*

large temperature differences, the resistances for LF-2 and LF-3 were remarkably similar, while those for LF-1 were some 20% lower. The reason for these differences is not known, but a possibility is differences in installation.

The shape of the resistance-temperature difference curves is characteristic of heat transfer by natural convection. For a horizontal porous medium heated from below, no convection is expected until a certain critical temperature difference is reached, after which the resistance starts to decrease with increasing temperature difference. The hypothesis of the occurrence of natural convection has been confirmed through infrared images of the top of the insulation (Wilkes et al. 1991a). These revealed a hexagonal pattern that is also characteristic of some natural convection configurations, with cold dense air from the attic flowing down into the insulation at the cores of the hexagons, being heated from below, and the warmer, less dense air flowing up out of the insulation at the perimeters of the hexagons. Qualitatively similar curves of resistance versus temperature difference have been observed for some other (but not all) currently used types of loose-fill fiberglass insulation (Rose and McCaa 1991; Larson 1992).

Theory shows that the onset of convection in a horizontal porous medium is governed by the dimensionless Rayleigh number, Ra, which is defined as

$$\mathrm{Ra} = \frac{g\beta\rho C_p L K \,\Delta T}{\nu k} \qquad (2)$$

where g is the acceleration of gravity; β, ρ, C_p, and ν are the volume expansion coefficient, density, specific heat, and kinematic viscosity of air; L, K, and k are the thickness, airflow permeability, and apparent thermal conductivity of the porous medium; and ΔT is the temperature difference across the porous medium.[1] The theories also predict that the critical Rayleigh number depends upon the thermal and mechanical boundary conditions imposed on the top and bottom surfaces of the insulation. For the configuration of attic insulation, with an open top surface, the critical Rayleigh number should be 27.1 or less. For the type of insulation used in these experiments, measured airflow permeabilities range from 6.7×10^{-7} to 1.0×10^{-6} ft^2 (Yarbrough 1990; McCaa 1990). For LF-2 and LF-3, convection appeared to begin at a temperature difference of 32°F and a mean temperature of 52°F, for which the critical Rayleigh numbers were 11 to 17. These values are in the same range as the value of 12 observed by Silberstein et al. (1990) using a box of loose-fill insulation and the values of 10 to 30 observed by Wilkes and Rucker (1983) using another attic test module.

Equation 2 implies that if the thickness is doubled, the critical temperature difference should be nearly halved (for the testing sequence used here, the critical temperature difference is not exactly halved because of the effect of differing mean temperature). Based on the results with LF-2 and LF-3, it would be expected that the critical temperature difference for LF-4 would be about 16°F. However, the data show about the same critical temperature difference for LF-4 as for LF-2 and LF-3. It is hypothesized that this is due to a combination of a higher density and a deviation from the conditions on which Equation 2 is based, namely a homogeneous porous medium. Loose-fill fiberglass insulation does not meet the condition of a homogeneous medium, since the bottom layers are compressed by the overlying layers of insulation. The higher density bottom layers have a lower airflow permeability than the top layers, resulting in a larger critical temperature difference than if the entire depth had the same permeability as the top layers. The fact that the critical temperature difference is nearly exactly the same for the two different thicknesses may just be fortuitous.

Another deviation from homogeneity occurs in the attic because of the wood ceiling joists buried in the insulation. Numerical calculations by Delmas and Wilkes (1992) have demonstrated that these form local warm spots in the insulation and trigger convection at lower temperature differences than would be obtained in their absence.

One final note concerning the Rayleigh number is that it is sensitive not only to temperature (through the variation of the thermophysical properties with temperature) but is also somewhat sensitive to atmospheric pressure (through the variation of density and kinematic viscosity with pressure). Decreases in thermal performance due to convection would be expected to be more severe for conditions with higher atmospheric pressures and less severe for conditions with lower pressures compared to those experienced in the tests at Oak Ridge. However, in the absence of experimental data on variations of performance with atmospheric pressure, this effect has been ignored in this paper.

Loose-Fill Fiberglass with Covering Materials

After the experiments had been performed with LF-2 by itself, the loose-fill insulation was covered with a white polyethylene film and this, in turn, was covered with one-inch-thick 1 lb/ft^3 fiberglass blankets. Comparing results with and without a covering at the same test conditions shows that the effect of the covering system was to increase the resistance by 33% to 120% and to decrease the heat flow by 24% to 51%, with the larger percentage changes occurring at the largest temperature differences.

The trend with the covering in place suggests that heat transfer by natural convection has been nearly eliminated,

[1] It should be noted that the temperature difference used to define the Rayleigh number is not exactly equal to the surface-to-surface temperature difference used to define the thermal resistance. However, since the thermal resistance of the gypsum board (about 0.45 h·ft^2·°F/Btu) is much smaller than the thermal resistance of the insulation in the absence of convection (about 20 to 40 h·ft^2·°F/Btu), the difference between these two ΔTs is only about 1% to 2% and is, therefore, ignored in the discussion of the onset of convection.

except possibly at the largest temperature difference. The increase in resistance with increasing temperature difference is due to a coincident decrease in mean temperature and, hence, a decrease in the contributions of thermal conductivity due to conduction and radiation. For the largest temperature difference, the effect of the covering system was to increase the thermal resistance from 11.0 to 24.3 hr·ft^2·°F/Btu, a difference that is much larger than the resistance of about 3.6 h·ft^2·°F/Btu that can be attributed to the one-inch-thick blankets alone. The effect of the covering is thought to be due to four factors operating in combination. First, the weight of the blankets compacted the loose-fill insulation by at least one inch. This increase in density would reduce convection due to a lower airflow permeability. Second, the thermal resistance of the blankets would lower the temperature difference across the loose-fill part of the composite, since part of the total temperature difference would occur across the blankets, also resulting in less convection (in effect moving back up the resistance-temperature difference curve). Third, the film and blankets would block direct flow of air between the attic space and the loose-fill insulation, causing any remaining convective loops to be confined to the loose fill itself. Since the flow resistance would be higher, this would lessen the heat transfer by convection. Fourth, the thermal resistance of the blankets would be added on to the thermal resistance of the loose fill.

Following completion of the experiments with LF-3 alone, R-19 fiberglass batts were laid on top of the specimen. Again, comparing results with and without a covering at the same test conditions shows that the effect of adding the batts was to increase the thermal resistance by 101% to 297% and to lower the heat flow by 47% to 72%, with the larger percentage changes being at the largest temperature differences. As with the covering system on LF-2, the covering with only batts also appeared to have completely eliminated the effects of convection over the temperature range investigated. Again, the increase in resistance at the largest temperature difference was much larger than the resistance of the R-19 batts alone and is thought to be due to the same four factors mentioned for LF-2. Using the permeability of 6 × 10^{-8} ft^2 measured by Vafai and Belwafa (1990) on a similar fiberglass batt product, the flow resistance for the R-19 batts was calculated to be about 7 to 10 times higher than for the uncompacted loose-fill insulation. Such a high flow resistance would effectively block the direct flow of air between the attic space and the loose-fill insulation.

Fiberglass Batts Only

With the attic insulated with 24-inch-wide R-19 fiberglass batts, the thermal resistance increased with increasing temperature difference by about 5%, a variation that can be attributed to the dependence of conduction and radiation on changes in mean temperature. The resistance was independent of temperature difference at the three coldest conditions. Extrapolation of a linear fit through the data points at the four highest mean temperatures gives thermal resistances of 18.4 and 21.1 at 75°F and 30.9°F mean temperatures. The first value is within 3% of the value of 18.9 that would be expected based on a simple parallel path calculation using an R-value of 19 for the insulation. The second value is only 3.4% higher than the value measured at this mean temperature, indicating that any effect of convection is very small.

Using the airflow permeability of about 6 × 10^{-8} ft^2 measured by Vafai and Belwafa (1990) for a similar product, a Rayleigh number of about 3 was calculated for the coldest conditions used here. Since this is so much lower than Rayleigh numbers of 10 to 30 at which convection should begin, it is thought that no convection occurred through the bulk of the insulation and that the plateau in the resistance-temperature difference curve at large temperature differences was due to a small amount of convection over the joists where the batts may not have been butted perfectly together. For batts with a resistance of R-38, the largest Rayleigh number for the conditions used here would be about 6, and again no convection would be expected.

Loose-Fill Cellulose Insulation

Results of the two series of tests with loose-fill cellulose insulation indicated that the thermal resistance increased slightly with increase in temperature difference. Since an opposite trend would be expected if natural convection were significant, it is concluded that convection was negligible in this type of cellulose. The linear variation of thermal resistance with mean temperature is typical of most insulations where conduction and radiation are the dominant heat flow mechanisms. The data also showed a decrease in thermal resistance of 6% to 10%, which can be attributed to the 9% decrease in thickness due to "settling."[2]

Yarbrough (1990) has measured airflow permeabilities of 2 × 10^{-8} to 7 × 10^{-8} ft^2 for this type of material. At the most extreme condition tested here, the Rayleigh number would be about 1 to 4. Since this is so much lower than Rayleigh numbers of 10 to 30 at which convection would be expected to begin, it is not surprising that no evidence for convection was observed. Since the Rayleigh number is proportional to insulation thickness, the Rayleigh number for an R-38 level of this material would be expected to be about 2 to 8 at the most extreme conditions, and, again, convection would not be expected.

ANALYSIS OF ANNUAL IMPACT OF CONVECTION

Analyses of the effects of convection on heating season loads and energy costs have been performed using a detailed dynamic attic model (Wilkes 1991a, 1991b). This

[2]A larger amount of settling, which might be expected in the field, would lead to larger decreases in thermal resistance.

model was modified by adding a subroutine that uses the experimental curves from Figure 3 (with a few extrapolations and linear interpolation between data points) to estimate the thermal resistance between the bottom of the gypsum board and the top of the insulation on an hourly basis, depending upon the temperature difference across the ceiling. The model was run for a 1540-square-foot prototypical attic (described by Wilkes [1991b]) using hour-by-hour Typical Meteorological Year weather data for 26 cities and the California Climate Zone data for Riverside, CA, with the inside temperature maintained constant at 70°F. Heat flows through the ceiling were counted as part of the seasonal load only if the outdoor temperature was below a specified balance point. Since balance points vary significantly, depending upon house insulation levels, airtightness, solar gains, and internal loads, calculations were performed with balance points ranging from 45°F to 65°F. A mid-range balance point of 55°F was selected for presentation of most of the results.

Table 4 gives annual ceiling heat loads in terms of Btu/ft^2·yr for a balance point of 55°F for each of the 27 cities and for each of the insulation systems studied. These heating loads were converted to energy dollars by dividing by an assumed natural gas furnace efficiency of 65% and multiplying by a national average natural gas cost of 58 cents per therm (100,000 Btu) (Nisson 1992). Heating costs in \$/ft^2·yr are plotted versus heating degree-days in Figure 4 for a balance point of 55°F. As shown by the example for Bismarck, ND, in Figure 5, the sensitivity of heating costs to house balance point is relatively small, especially if the primary interest is in differences between levels and types of insulation. Since the heating costs differ from the seasonal heating loads by a constant factor, plots of seasonal heating load would have identical shapes. Above about 3000 heating degree-days, the curves have very regular shapes. The curves for the batts alone, the two loose-fill fiberglass specimens with coverings, and the cellulose are very linear, but the curves for the loose-fill fiberglass insulations alone have a definite upward hook at large degree-days. Above 3000 heating degree-days, none of the curves cross each other. From the highest to the lowest energy costs, the cases are ordered as follows: (1) loose-fill fiberglass Specimen 2, R-19; (2) loose-fill fiberglass Specimen 3, R-19; (3) R-19 cellulose, "settled"; (4) R-19 batts; (5) R-19 cellulose, as blown; (6) loose-fill fiberglass Specimen 2 with the covering system; (7) loose-fill fiberglass Specimen 4, R-38; and (8) loose-fill fiberglass Specimen 3 covered with R-19 batts. It should be noted that this ordering is a little different from the ordering of resistances at the highest temperature differences shown in Figure 3 and is closer to the ordering at low temperature differences, illustrating the significance of performing an annual analysis.

While there are many ways to estimate the effect of convection, the method chosen here was to take the difference between curves for loose fill and batts of the same nominal R-value. For purposes of illustration, annual energy costs for the most extreme case studied, Bismarck, ND, will be discussed; costs for other cities may be easily obtained from Table 4 and Figure 4. An approximation for the R-19 level may be obtained by comparing the curves for LF-2 and LF-3 with the curve for R-19 batts. For Bismarck (9022 heating degree-days), the difference is about \$0.024 to \$0.029 per square foot per year, or an increase of 25% to 30%. This difference would be smaller for milder climates.

For Bismarck, the effect of adding the covering on LF-2 is to decrease the annual heating cost by \$0.044 per square foot. Similarly, the effect of adding R-19 batts to LF-3 is to decrease the annual heating cost by \$0.070 per square foot, and the effect of increasing the level of loose-fill insulation from R-19 to R-38 is to decrease the annual heating cost by \$0.056 to \$0.061 per square foot. A rough approximation for the effect of adding R-19 batts over existing R-19 batts may be obtained by comparing the heating costs for R-19 batts alone with that for LF-3 covered with R-19 batts; this gives an annual heating cost decrease of \$0.046 per square foot. Finally a rough approximation for the effect of convection at the R-38 level may be obtained by comparing the curves for LF-4 with that for LF-3 covered with R-19 batts, giving \$0.014 per square foot per year.

SUMMARY AND CONCLUSIONS

A series of experiments has been completed on the thermal performance of fiberglass and cellulose attic insulations under winter conditions using an attic test module in a guarded hot box facility. Experiments with one type of loose-fill fiberglass insulation at both the R-19 and R-38 levels showed that the thermal resistances started to decrease when the temperature difference between the bottom of the gypsum board and the top of the insulation exceeded about 32°F. As the temperature difference increased above this value, the resistance continued to decrease until, at a temperature difference of 70°F to 76°F, the resistance was reduced by about 35% to 50%. The decrease in resistance has been attributed to heat flow through the insulation caused by natural convection. Experiments with R-19 loose-fill fiberglass insulation covered either with a combination of a polyethylene film and one-inch-thick fiberglass blankets or with R-19 fiberglass batts showed that the covering effectively eliminated heat flow by natural convection. Although the covering system with a polyethylene film was effective in eliminating convection, this exact configuration is not recommended for cold climates because of the potential for moisture condensation; some degree of perforations would probably be necessary. Experiments with the attic insulated only with 24-inch-wide R-19 batts also showed that there is no significant convection in the bulk of the insulation over the temperature range investigated. No convection in R-19

TABLE 4
Calculated Annual Heating Load for Attics Insulated with Fiberglass or Cellulose Insulation, Assuming a House Heating Balance Point of 55°F

CITY	HDD65	Annual Ceiling Heating Load, Btu/ft^2•yr							
		LF-2, R-19	LF-3, R-19	LF-4, R-38	LF-2 + Blankets, R-23	LF3 + R-19 Batts, R-38	R-19 Batts	R-19 Cellulose, As-Blown	R-19 Cellulose, "Settled"
Albany, NY	6805	9859	9306	4972	6939	4377	8161	7975	8640
Albuquerque, NM	4452	6577	6107	3249	4850	3076	5685	5561	6049
Atlanta, GA	3099	4499	4108	2173	3386	2146	3958	3869	4230
Bismarck, ND	9022	14172	13665	7377	9286	5814	10938	10644	11463
Chicago, IL	6195	8832	8293	4385	6292	3969	7404	7238	7856
Denver, CO	6114	9111	8540	4549	6521	4120	7659	7486	8127
El Toro, CA	1590	2900	2601	1397	2236	1422	2588	2529	2774
Houston, TX	1363	2100	1895	1010	1602	1016	1864	1821	1997
Knoxville, TN	3852	5603	5178	2758	4141	2623	4844	4738	5162
Las Vegas, NV	2415	3813	3476	1848	2898	1843	3380	3304	3610
Los Angeles, CA	1507	2039	1819	984	1574	998	1817	1775	1951
Memphis, TN	3300	4724	4329	2298	3539	2242	4136	4044	4415
Miami, FL	189	315	282	151	243	154	281	274	301
Minneapolis, MN	8095	12272	11785	6332	8180	5129	9637	9395	10130
Orlando, FL	543	933	835	448	718	455	832	812	892
Phoenix, AZ	1391	2549	2313	1231	1949	1240	2267	2216	2423
Portland, ME	7353	10746	10101	5395	7592	4788	8915	8708	9447
Portland, OR	4602	6703	6056	3216	5106	3234	5944	5808	6366
Raleigh, NC	3550	5219	4809	2557	3884	2464	4545	4445	4847
Riverside, CA	2083	4150	3795	2034	3153	2011	3672	3591	3919
Sacramento, CA	2755	4639	4182	2237	3551	2255	4123	4029	4416
Salt Lake City, UT	5989	8559	7955	4219	6232	3942	7315	7148	7780
St. Louis, MO	4899	7171	6679	3533	5201	3284	6106	5970	6495
Seattle, WA	5300	7514	6769	3584	5732	3626	6674	6519	7154
Topeka, KS	5247	7976	7521	4019	5619	3545	6605	6454	6995
Waco, TX	2203	3341	3038	1610	2526	1600	2948	2881	3153
Washington, D.C.	4866	7076	6574	3502	5175	3276	6065	5930	6451

HDD65 = heating degree days, base 65°F.
LF-2, LF-3, LF-4 = loose-fill fiberglass Specimens 2, 3, 4.
A constant indoor temperature of 70°F was assumed.

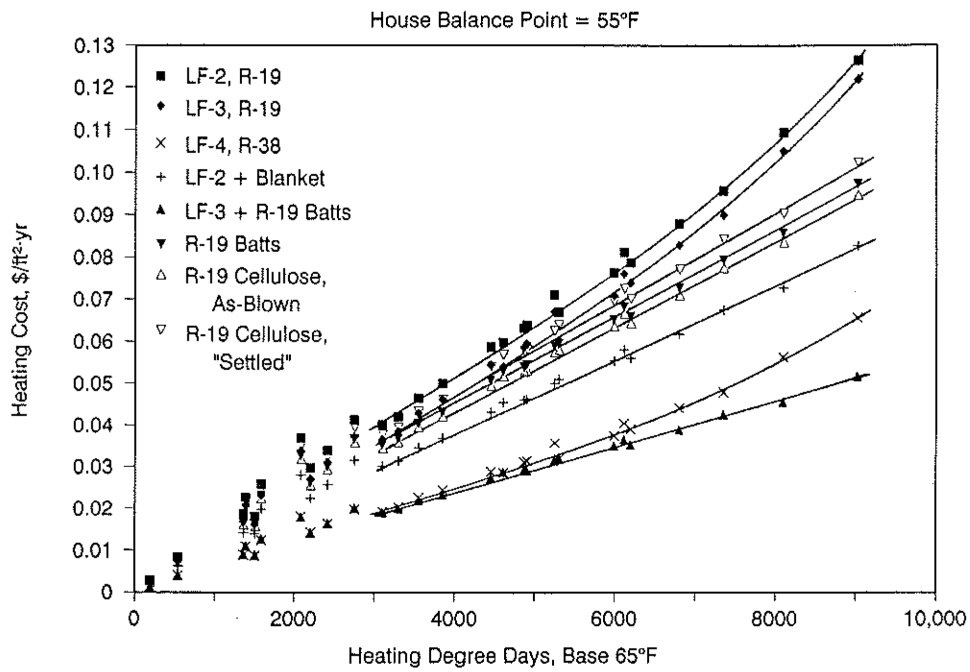

Figure 4 *Estimated annual heating energy costs for attics insulated with different materials. The ordinate is the annual energy cost per square foot of ceiling. The abscissa is the heating degree-days, base 65°F. A constant indoor temperature of 70°F and a house balance point of 55°F were assumed.*

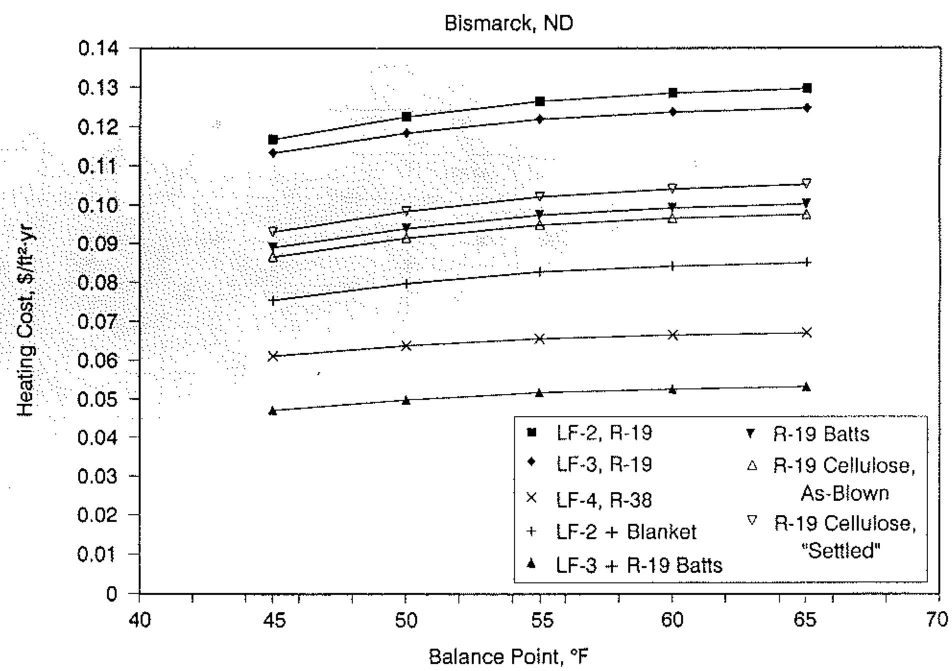

Figure 5 *Effect of house balance point on annual heating energy costs for attics insulated with different materials in Bismarck, ND. A constant indoor temperature of 70°F was assumed.*

loose-fill cellulose material was found under the conditions studied.

The experimental resistance-temperature difference curves were used in a detailed hour-by-hour thermal model for attics along with hourly weather data for 27 cities in the lower 48 states of the U.S. to calculate hourly heat flows through the ceiling and to estimate annual energy costs. In the coldest climate investigated, Bismarck, ND, the additional energy costs due to convection were estimated to be $0.024/ft^2·yr to $0.029/ft^2·yr at the R-19 level and about $0.014/ft^2·yr at the R-38 level. For the same conditions, annual energy savings due to upgrading insulation from the R-19 to the R-38 level were estimated to be $0.046/ft^2·yr to $0.070/ft^2·yr.

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