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Measured Values of Temperature and Sheathing Moisture Content in Residential Attic Assemblies

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ABSTRACT

A test facility has been constructed to measure heat transfer, moisture movement, and airflow in typical residential attic assemblies under natural conditions. The laboratory contains eight study bays with different configurations of ceiling structure (flat vs. cathedral), ventilation (with venting vs. without venting), ceiling penetration (with openings vs. without openings), shingle color (white vs. black), and cathedral ceiling insulation placement ("slotted" vs. "stuffed"). The interior space beneath the study attics is maintained at uniform temperatures during summer and winter. During the winter, the interior space is humidified. The laboratory is equipped to monitor weather, temperature, humidity, moisture content, heat flux, pressure difference, and air movement. Hourly data have been collected continuously for two years.

The purpose of this paper is to present and explain two sets of data: (1) temperature of the sheathing and attic cavity during summer and (2) moisture content of the sheathing during winter. To explain the data, the details of construction are described, and the characteristics of the instruments used for measurement and data acquisition are presented.

BACKGROUND

The effectiveness of attic ventilation has been the subject of much speculation and little study. The first scientific studies on attic performance were conducted in an environmental chamber at the University of Minnesota by Professor Frank Rowley (1939), who found "For cold attic spaces, it is desirable to allow openings for outside air circulation through attic space as a precaution against condensation on the underside of the roof even though barriers are used in the ceiling below." The first publication of attic venting "ratios" appeared in two publications by the Small Homes Council (University of Illinois), "Insulation" (Konzo et al. 1946) and "Moisture Condensation," authored by Rowley (1947).

Beginning in 1947, the Housing and Home Finance Agency (HHFA) sponsored work at Penn State under the direction of Ralph Britton. The Penn State researchers (including Hechler, Queer, and McLaughlin) constructed a building with wall test panels and three roof test panels that fitted tightly within a 20-ft-by-22-ft (6.1-m-by-6.7-m) climatometer. Panels 1, 2, and 3 had rock wool insulation; panel 3 had no vapor barrier. Each of the panels had a 5/16-in. (0.8-cm) slot at each end. The vent-to-roof area ratio, 1/300, appears to have been an incidental detail, peculiar to the test setup. Conditions at the "interior" were kept at 70°F (21°C) and 38% rh; "outdoor" conditions were 0°F (-18°C) and 78% rh.

It was found after two weeks in the climatometer that roof panels 1 and 2 remained dry. However, roof panel 3 had frost on the deck near the center but none near the eaves. Britton (1947) suggested in the in-house report that "1/300th of the reflected roof surface may not be sufficient ventilation to prevent condensation in flat roofs...where there is no effective vapor barrier on the warm side of the insulation." Another series of tests was conducted, then the project was discontinued for lack of funds. It is interesting to note that the standard rule of thumb for the ventilation of attic assemblies (the 1/300 ratio) arose from incomplete work on flat roof panels within a steady-condition climatometer with no simulation of radiant effects and no provision for either mechanically induced or natural airflow.

In 1962 Hinrichs (1962) compared the performance of various vent types. He also noted the relative importance of air leakage over diffusion as a moisture transport mechanism. Little attic research was done until the 1980s. Ford (1982), taking measurements in a test hut, noted the strong effect that temperature has on the absolute humidity in attics. Cleary (1984) explained similar findings as the effect of temperature-driven moisture storage and release in wood materials. An experimental and modeling effort on attic assemblies was conducted by Burch et al. (1984) which confirmed the importance of moisture storage and release in overall performance. Harrje et al. (1985) made intermittent moisture content measurements in two occupied houses in New Jersey and were able to confirm large seasonal variations. Currently, Forest et al. (1990) are conducting a rigorous study on attic performance under natural conditions, focusing on wind effects.

AIM

The aim of this paper is to present and explain the measurements of temperature and sheathing moisture content that have been taken at a building research laboratory. The aim is to answer the questions, "How hot does a

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roof get?" and "How wet does the material in a roof get?"

This presentation is part of a larger continuing research effort aimed at characterizing the overall performance of typical residential attic assemblies under natural conditions. The task of characterizing the overall performance of attics involves the measurement of several parameters: temperature, moisture content, relative humidity, airflow, air change rate, heat flux, pressure difference, energy consumption, etc. Only temperature and moisture content data will be presented here.

This paper does not aim to model roof performance or to compare the variety of venting strategies or venting products. Rather, it seeks to establish what happens in only two cases of venting: with and without vent devices in place.

This paper does not propose changes to current building practice or building codes. Whether such changes are or are not appropriate is a decision best left to organizations suited to deal with the multiplicity of conflicting interests such proposals entail. However, it is hoped that these results are formatted in a way that will be helpful to those studying changes to practices and codes. A study of these results may lead to a greater understanding of performance tradeoffs, which may increase the range of design options.

SETUP

During 1989, a laboratory building, shown in the photo of Figure 1, was designed and constructed on an exposed site in central Illinois. The building is located on a slight rise, 200 ft (60 m) from other buildings and treelines. There is a weather station on the site and a station of the National Weather Service located 1/4 mile (400 m) away.

The plan of the building is shown in Figure 2. It contains eight study bays, each 20 ft by 8 ft (6.1 m by 2.4 m), with conditioned buffer bays on the two ends. The ridge runs east and west. Five study bays, numbered 1 through 5, are of flat-ceiling truss-framed construction, and three bays, numbered 6 through 8, are of cathedral ceiling construction.

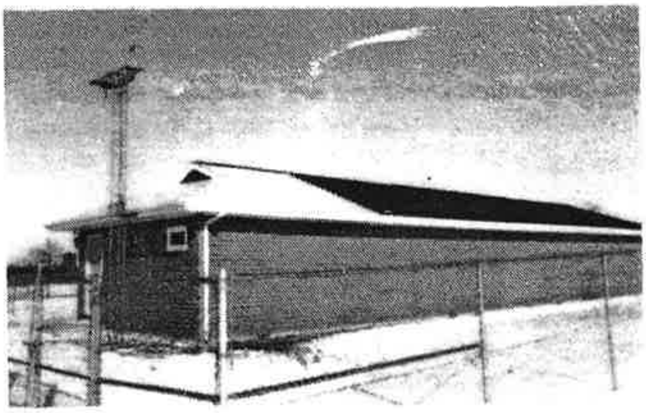


Figure 1 *Photograph of the building research laboratory.*

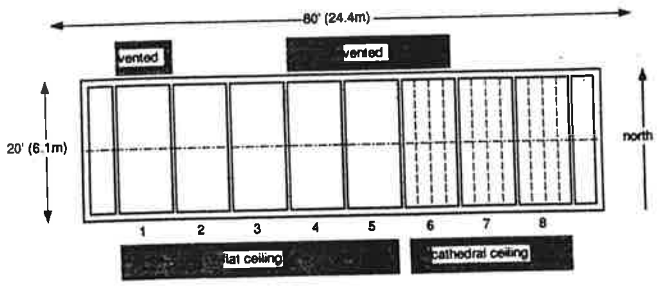


Figure 2 *Plan of the building research laboratory.*

It had been the intent of this project to construct study bays where the effect of workmanship variations would be negligible. One cannot afford to ignore the impact of workmanship on the performance of light frame construction assemblies. During construction, the builders were instructed to divide the construction into separate tasks that could be done in a single day. The builders were encouraged to work at a uniform rhythm. After construction, the airtightness of the individual bays—both indoor volumes and flat-ceiling attic volumes—was tested using pressurization and air change techniques (CMHC 1991). The indoor volumes were found to be of uniform leakage areas. The two vented attic volumes showed similar airtightness (within 10% ELA), as did the two unvented attic volumes. In addition, during the first year, paired bays (2 and 3, 4 and 5) showed practically identical temperature performance.

The construction details were selected to be typical of construction common in the Midwest. The foundation is a crawl space; the wall framing is of 2-by-4 construction with insulating sheathing and a polyethylene vapor retarder. The roof pitch is 5:12, the roof overhang is 2 ft (.6 m), the exterior cladding is vinyl, and the shingles are reinforced asphalt triple-tab.

The interior of each bay is faced with 1/2-in. (12-mm) drywall, with two coats of interior latex flat wall paint. Each bay is individually heated, cooled, and humidified. During the summer, the interior temperature is thermostatically controlled at 75°F (24°C). During winter, the interior is kept at 70°F (21°C) and humidified to 50% rh.

A typical eave section for a flat-ceiling bay is shown in Figure 3. Details of the configuration of each of the study bays are given in Tables 1 and 2. Briefly, the principal variables under study are

- ceiling construction (flat vs. cathedral),
- venting (with vs. without ridge and soffit vents),
- airtightness of the ceiling (capped vs. uncapped openings in the ceiling),
- cathedral ceiling insulation placement ("slotted" vs. "stuffed").

The "slotted" cathedral ceilings are constructed with 10-in. (254-mm) batt insulation (R-30) in the 11 1/4-in. (286-mm) cavity, leaving a continuous air slot along the underside of the sheathing. The "stuffed" cathedral ceilings

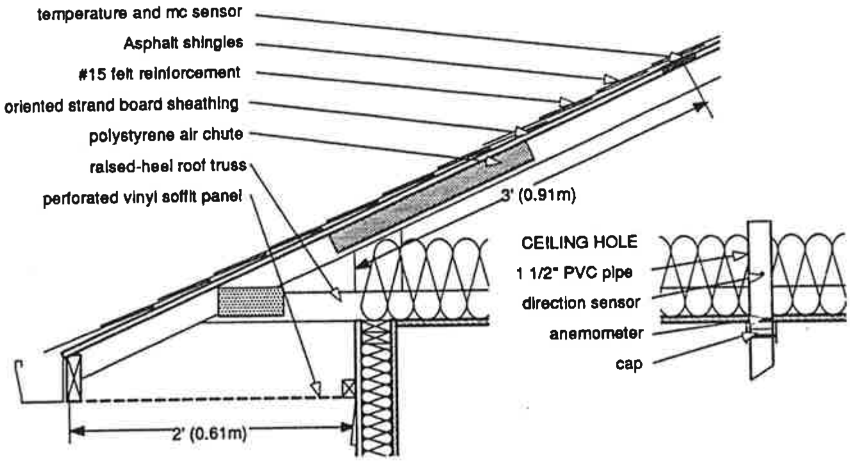


Figure 3 *Eaves section of the vented, flat-ceiling bay at the building research laboratory, showing construction details, placement of the air chute, sensor location, and detail of the ceiling hole.*

TABLE 1
Details of Construction by Component

Component	Description
Roofing	Reinforced asphalt triple-tab shingles over #15 felt underlayment. White shingles on Bay 1; black shingles on all other bays.
Sheathing	7/16" oriented strand board (OSB) nailed to framing. Foil-faced polyisocyanurate insulation, 1 in. thick, beneath sheathing in bay 8 only.
Framing	Pre-engineered trusses at 2' o.c. in flat-ceiling bays 1, 2, 3, 4, and 5. Dimension lumber 2x12 rafter framing at 2' o.c. in cathedral-ceiling bays 6, 7, and 8.
Vapor retarders	No vapor retarders in the ceilings of bays 1, 2, 3, 4 and 5. Cathedral ceiling bays 6, 7, and 8 have kraft insulation facing face-stapled to the undersides of the rafters. The kraft facing is discontinuous at 4' intervals.
Insulation	R-30 unfaced fiberglass batt insulation in bays 3 and 5. Loose-fill fiberglass insulation blown to R-30 in bays 2 and 4. Kraft faced R-30 fiberglass batt insulation in the "slotted" cavities of bays 6 and 7 and in all of the cavities of bay 8. R-38 fiberglass insulation in the "stuffed" cavities of bays 6 and 7. The R-38 insulation is composed of an upper batt of R-19 fiberglass from which the kraft facing was removed, and a lower batt of R-19 fiberglass with the kraft facing intact.
Ceiling opening	PVC piping, 1 1/2" diameter, extending through the ceiling and insulation. Each opening is equipped with a plumbing fitting cap which can be removed. Each opening is instrumented with an anemometer and a thermocouple, used to compare the pipe temperature with the room and attic temperatures in order to indicate flow direction.
Vent devices	Bays 1, 4, 5, and 6, contain ridge and soffit venting devices. The ridge vents are shingle-covered polymer devices with a fiberglass filter and a baffle which screens the opening. The soffit vents are vinyl panels with 1/8" diameter perforations. The vent-to-area ratio is approximately 1/150. Bays 2, 3, 7 and 8 have cap shingles in place of ridge vents, and have no perforations in the soffit panels.
Attic partitions	The flat-ceiling attics are separated thermally by 1" of foil-faced polyisocyanurate panels fastened to the common truss. Cracks are foamed shut with a urethane foam. A gasketed hatch is used to provide access from the interior of bay 0 to the attic of bay 1 and from one attic space to another. In the cathedral ceilings, there is no gap which would allow air movement among any of the four cavities in each bay. There is no access to the cathedral ceiling cavities.

TABLE 2
Construction Details by Bay: 1991-1992

Bay #	Ceiling	Roof	Vented	Insulation
1	flat	white	yes	batt
2	flat	black	no	loose-fill
3	flat	black	no	batt
4	flat	black	yes	loose-fill
5	flat	black	yes	batt
6	cathedral	black	yes	slotted/stuffed
7	cathedral	black	no	slotted/stuffed
8	cathedral	black	no	1" rigid + batt

are constructed with two thicknesses of 6 1/4-in. (159-mm) insulation, each R-19, which completely fill the cavity.

INSTRUMENTATION

Surface Temperature

Type-T thermocouples are used to make temperature measurements of the sheathing. All thermocouple wire is of the same length and from the same source. The thermocouples are measured at three data acquisition units, each with a thermistor reference junction. A fifth-order polynomial resident in the data-acquisition unit converts EMF to temperature. Possible sources of error include voltage reading precision and accuracy, polynomial approximation, variations in thermocouple wire, and reference junction precision and accuracy. Where two temperatures are being compared, the largest source of error, reference thermistor accuracy, does not apply.

Each bay contains eight sheathing thermocouples, distributed evenly as follows:

- north slope/south slope,
- low (3 ft [0.9 m] up from the eaves)/high (3 ft [0.9 m] down from the ridge),
- topside (between sheathing and felt roof underlayment)/ underside (fastened beneath the sheathing).

In other words, the eight thermocouples represent the eight (2^3) possible combinations of the three conditions: north/south, low/high, and topside/underside. The cathedral ceiling bays have 16 thermocouples (2^4) representing the variables described above, plus the variable condition of "slotted"/"stuffed."

Air Temperature

Measurements of air temperature in the attic space and cathedral ceiling cavities are taken using platinum resistance temperature detectors (RTD). Each RTD is located near the ridge and is radiant protected. The RTDs receive an excitation voltage of 2000 mV, and the output is read across a 1 kOhm resistor of 1% tolerance maintained at uniform (indoor) conditions.

Moisture Content

Making continuous remote measurements of wood product moisture content is a research problem of classic difficulty.

This research made use of electrical resistance techniques developed by Duff (1966), who describes the use of small maple blocks 1/16 in. by 1/16 in. by 1/2 in. (1.6 mm by 1.6 mm by 12 mm) with electrodes fastened to opposite sides. After fabrication, the block probe is embedded in a wood product. The electrodes from the probe are connected to a bridge capable of making electrical resistance measurements up to several hundred megohms. The electrical resistance of the block decreases logarithmically with increases in moisture content. The relationship between resistance and moisture content is shown in a chart in the Wood Handbook (FPL 1987). The advantages of the electric resistance technique include

- *site specificity*—the block is considered to be in equilibrium with the small volume of wood surrounding it;
- *simplicity*—the technique is generic and can be customized to various applications;
- *track record*—electrical resistance measurements for spot measurements have been in widespread use for decades with considerable confidence; and
- *low cost*—this research project required the use of 80 sensors.

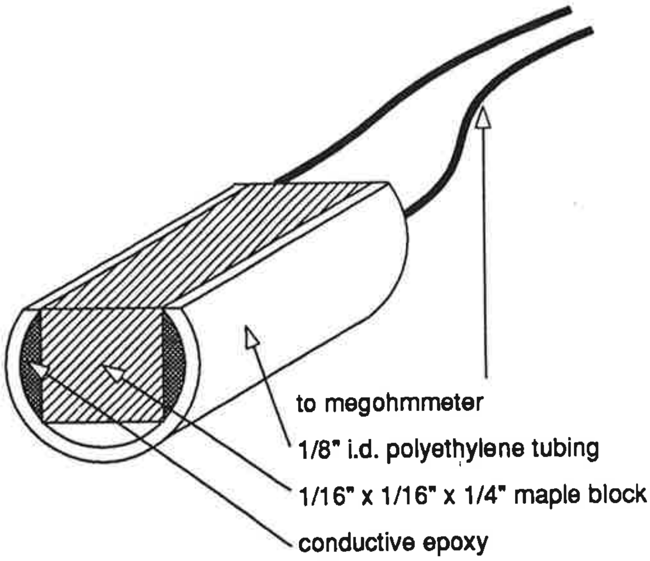
However, there are significant disadvantages in the use of resistance measurements. They include

- *interchangeability error*—different sensors may give different readings for the same conditions due to variations in grain of the probe;
- *large capacitance effects*—requiring a delay in the electrical response;
- potential for *polarization of the resistor* over time; and
- uncertainty in *converting resistance to moisture content* for various wood products.

Figure 4 shows the sensor that was developed. Twice the desired number of sensors were fabricated by hand. A thin, long (1/16 in. by 1/16 in. by 6 in., (1.6 mm by 1.6 mm by 150 mm) rod of maple was milled to dimension. Two opposite sides were painted with conductive epoxy, and then the rod was carefully slipped into a 6-in. (150-mm) length of polyethylene tubing. Already-prepared electrodes were slipped into the uncured epoxy at the end of the rod, and that end was cut from the remaining rod with a jeweler's saw. This process was repeated until each rod provided approximately 20 small 1/4-in. (6.4-mm) -long sensors. After the epoxy had cured, a scalpel was used to cut the tubing, exposing one face of maple.

For calibration, the sensors were placed in a controlled chamber, and the electrode leads were attached to a multiplexer and bridge. The conditions of temperature and humidity within the chamber were varied over a two-week period. The outlying sensors (with signals outside the response of the others) were identified and discarded.

The probes were installed in the sheathing in pairs at each of four monitoring locations in each bay. In each pair, one probe was an "embedded" probe and the other a "surface" probe. The embedded probe was installed by drilling a hole in the sheathing almost through the sheathing, then inserting the probe; the exposed surface of the probe faces the thickness of the sheathing material. The surface probe was installed by routing a slot on the attic side of the sheathing and inserting the probe so that the exposed face remains flush with the underside of the sheathing (see Figure 4, insert). The need for a probe to



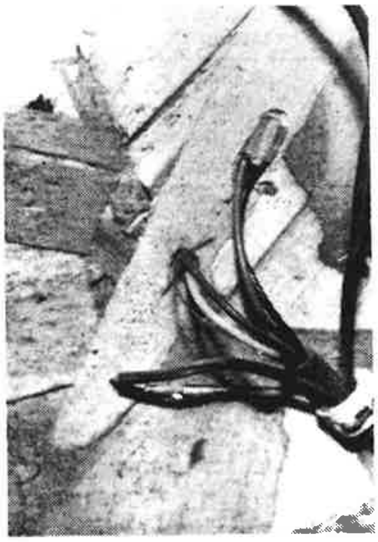


Figure 4 *Moisture content probe, based on the moisture probe of Duff (1966). Insert: photograph of moisture content probes in place showing embedded and surface sensors.*

indicate sheathing surface effects was indicated by the research of Burch (1984). The embedded probe was inserted into the OSB with air contact rather than wood contact for two reasons: (1) out of concern that the material heterogeneity of the OSB would introduce unnecessary error into the resistance readings and (2) to enhance the similarity of conditions between the surface probe and the embedded probe.

During the first winter of measurements, beginning January 1991, the resistance in the sensor was determined by exciting each sensor with a 2000 mV signal, then reading the voltage drop across a reference resistor (1 megohm, 1% tolerance) in series with the sensor, after a delay of 10 msec. The delay time was determined empirically after trials at different delay times. The voltage drop across the probe was converted to resistance, and the resistance values were stored. After making the resistance measurement, a signal of 2000 mV with reversed polarity was sent to each sensor. This was done to decrease the likelihood of polarization error in the sensors. The stored value is a resistance value, not a moisture content value. To actually convert resistance to moisture content for the sheathing material—oriented strand board—would require making gravimetric measurements and electric resistance measurements of the same samples to develop a correlation. To date, this work has not been carried out. Instead, the units' logarithm_{10} of the resistance (megohms) are used in the analysis of the data as a standard indicator of wood product moisture content.

During the second winter, beginning December 1991, Delmhorst meters were installed to replace the resistance bridges used during the previous winter. The voltage output from the moisture meter was converted to moisture content using curves supplied by the meter manufacturer. Temperature measurements were taken at the locations of each moisture content probe, and the temperature corrections provided by the meter manufacturer were applied.

The sources of possible error in the moisture content measurements are considerable. The interchangeability error among the individual probes was found, during calibration, to be approximately 4%. Data from the first winter have not been converted from resistance to moisture content. The validity of moisture content values from the second winter rely heavily on conversion coefficients from the meter manufacturer.

Polyimide capacitance relative humidity sensors were installed adjacent to each air temperature sensor. The output from these sensors bears a complex relation to the moisture content readings, largely because moisture is constantly being exchanged between the wood and the air cavity. The relative humidity data are not included in this analysis.

Data Acquisition

Three data acquisition units are used. They are programmed to sample each sensor at 10-minute intervals and then average these values as hourly data. Hourly data from 370 sensors are stored in the data-logging units and the data are transferred weekly to computer storage. The data are archived, copied to off-site storage, and processed to prepare a weekly report.

FINDINGS

Dates of each study period are shown in Table 3. The amount of data lost to power outages and reprogramming of the data acquisition units can be seen as being minor.

TABLE 3

Test Period	Starting Date	Ending Date	Missing Data	Scope
First Winter	December 30, 1990	February 24, 1991	None	Flat ceilings
First Winter	January 28, 1991	February 24, 1991	None	Cathedral ceilings
Summer 1991	June 1	August 31	June 25-30	Both
Second Winter	December 1, 1991	February 29, 1992.	None	Both

Temperature

The data presented here are from summer 1991. They are essentially similar to the temperature findings of the previous summer.

Figure 5 shows maximum temperatures of the sheathing during the summer. These maximum temperatures were not concurrent; that is, each value represents the maximum for the sensor location, drawn from the entire data set of summer values.

The highest sheathing temperature, 185°F (85.3°C), was measured on the south face of the cathedral bay (8) with 1 inch of isocyanurate foam insulation directly beneath the sheathing. The measurement was taken on the top side of the sheathing between the sheathing and felt underlayment under black shingles. All other cathedral ceiling sheathing reached maximum temperatures above 180°F (82.2°C) except the case with venting and a continuous slot for air movement (170°F [76.8°C] maximum). The sheathing of flat ceiling attics did not reach temperatures as high as those in the cathedral ceilings. We may select one condition as a baseline: the maximum sheathing temperature of the top side, south side of an unvented flat-ceiling attic with black shingles—174.7°F (79.3°C). Compared to that condition,

- the vented attic sheathing was almost 10°F (5.5°C) cooler,
- the underside of the sheathing was 12°F (6.6°C) cooler,
- the north side slope was 11°F (6.1°C) cooler, and
- the sheathing under white shingles, vented, was 26°F (14.4°C) cooler.

Figure 6 shows the maximum air temperature of flat-ceiling attics and cathedral ceilings for the same summer. It can be seen that the effect of ventilation is greater on the attic air temperature than on the sheathing temperature. Compared to the maximum attic air temperature in the unvented flat-ceiling bay, 158.6°F (70.3°C),

- the attic air temperature in the vented attic is 28°F (15.5°C) cooler,
- the attic air temperature in the vented attic with white shingles is 32°F (17.8°C) cooler,
- the vented cathedral ceiling cavities are 7°F (3.9°C) cooler (slotted) and 3°F (1.6°C) cooler (stuffed),
- the unvented cathedral ceiling cavities are 3°F (1.6°C) warmer (stuffed) and 8°F (4.4°C) warmer (slotted).

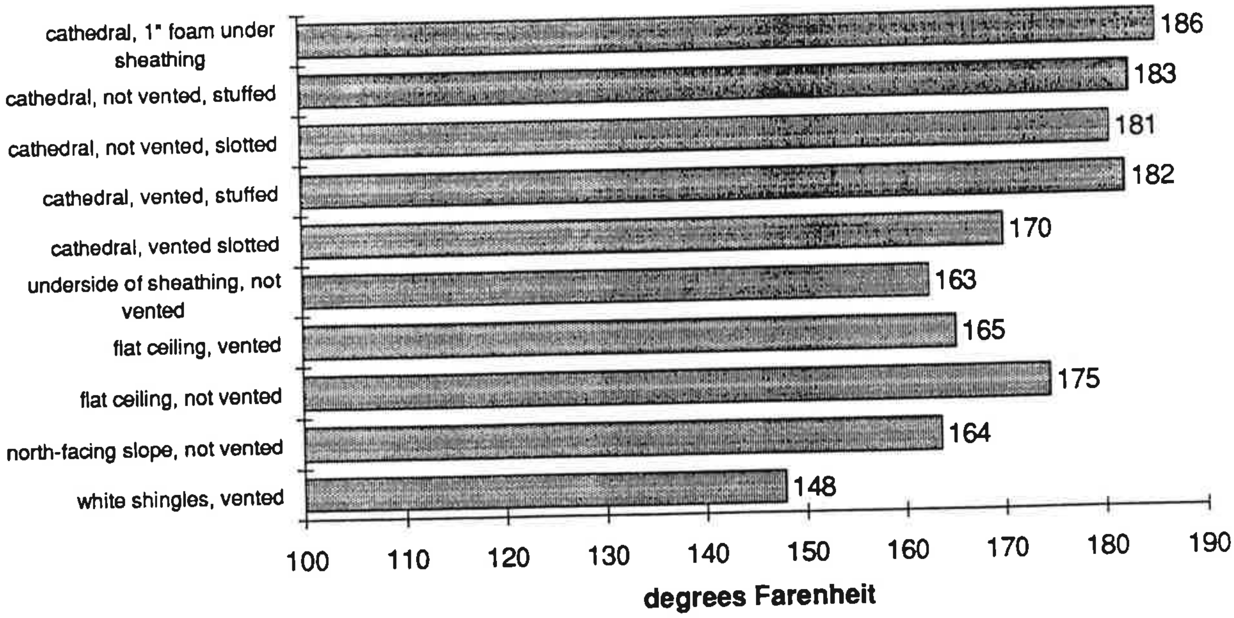


Figure 5 Maximum attic sheathing temperature for summer 1991. Temperature readings are not concurrent.

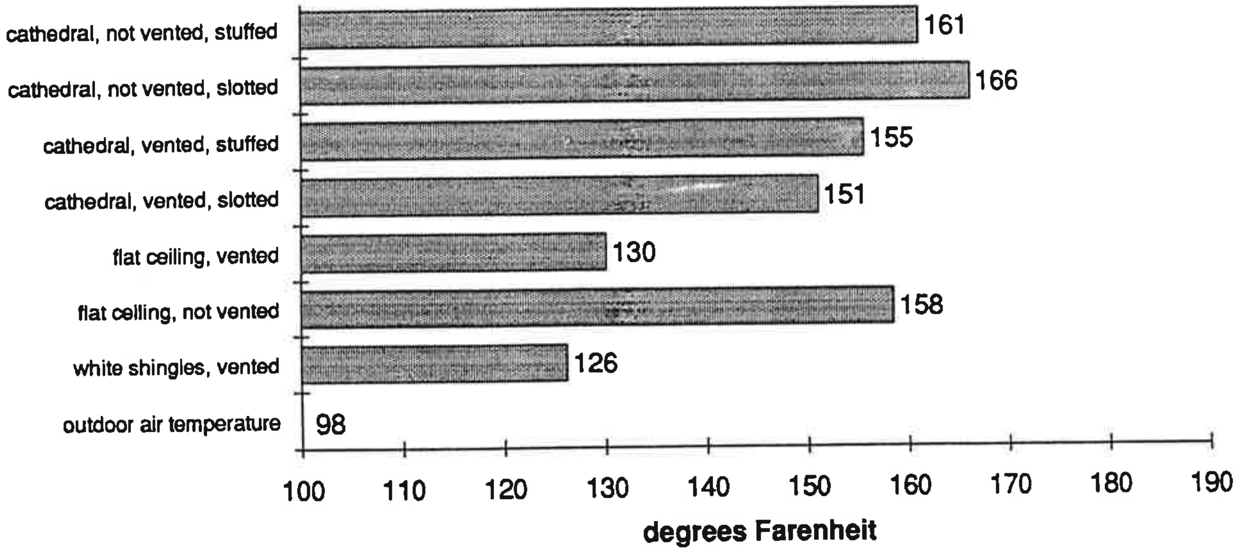


Figure 6 *Maximum air cavity temperature for summer 1991.*

Temperatures during the summer have been compiled to create a temperature distribution profile (histogram) showing the number of hours during the summer when the sheathing temperature was within a given 10°F (5.5°C) interval. Differences among the different attic configurations during summer are significant and interesting only at the high-temperature end of the distribution profile. The high-temperature end of this histogram is expanded in Figures 7 and 8. Figure 7 shows the number of hours during which various configurations of *flat* ceiling attic sheathings were above 120°F (49°C); Figure 8 shows the same results for *cathedral* ceilings. It can be seen that the unvented flat-ceiling sheathing temperature was subject to the greatest number of hours above 140°F (60°C). Among the cathedral ceiling cases, only the vented, slotted case showed significantly cooler sheathing temperatures.

The flat ceiling data are from batt insulation bays. The loose-fill insulation bays showed comparable summer attic air temperatures. During the winter, the batt insulation bays showed slightly lower attic air temperatures and slightly lower energy use (1.1% lower from January to March 1991) than the comparable loose-fill insulation bays. To resolve speculation regarding convection in loose-fill insulation, analysis of the still-preliminary heat flux data is continuing.

Moisture Content: Flat Ceiling Bays

Data from the first winter of measurement are shown in Figure 9. This figure is a histogram showing the number of hours during which the flat-ceiling bay sheathing was at a given moisture content. Interpretation of the meaning of "moisture content" in this chart should be subject to the cautions expressed above under "INSTRUMENTATION, Moisture Content." Values above 1 (indicating resistance less than 1 megohm) may be interpreted as indicating moisture content above 18%, using the relation shown in the *Wood Handbook* (FPL 1987).

The most commonly occurring indicator of moisture content (1/log(resistance) = 0.4) corresponds to 13% moisture content. Resistance values less than 1 megohm (indicating moisture content greater than 18%) occurred rarely and only in the unvented bays. There was no significant accumulation of moisture in any of the flat ceiling bays.

However, frost was seen to occur on the protruding nail points and on the panel clips. There were three frost events during the month of January 1991. Each of these events occurred during the coldest weather when outdoor temperature was less than 10°F (−12°C). The water appears to have diffused through the semi-permeable but airtight ceilings from 50% RH conditions below. During each of these three frost events, which were photographed, the accumulation of frost on the underside of the sheathing in the unvented bays was noticeable, while the accumulation in the vented bays was negligible. The observation of frost coincides in time with the recorded lowering of resistance below 1 megohm.

Figure 10 shows a histogram of the same conditions for the second winter. For the second winter, Delmhorst meters were used in the place of resistance bridges, and the output was in moisture content, as described above. The profiles for the three cases—vented, unvented, and white shingles (vented)—coincide closely. There is no evidence of accumulation of moisture above 22% moisture content. The winter was particularly mild. Only one event of frost accumulation on protruding nail points was observed. As before, the frost accumulation was somewhat greater in the unvented bays than in the vented bays.

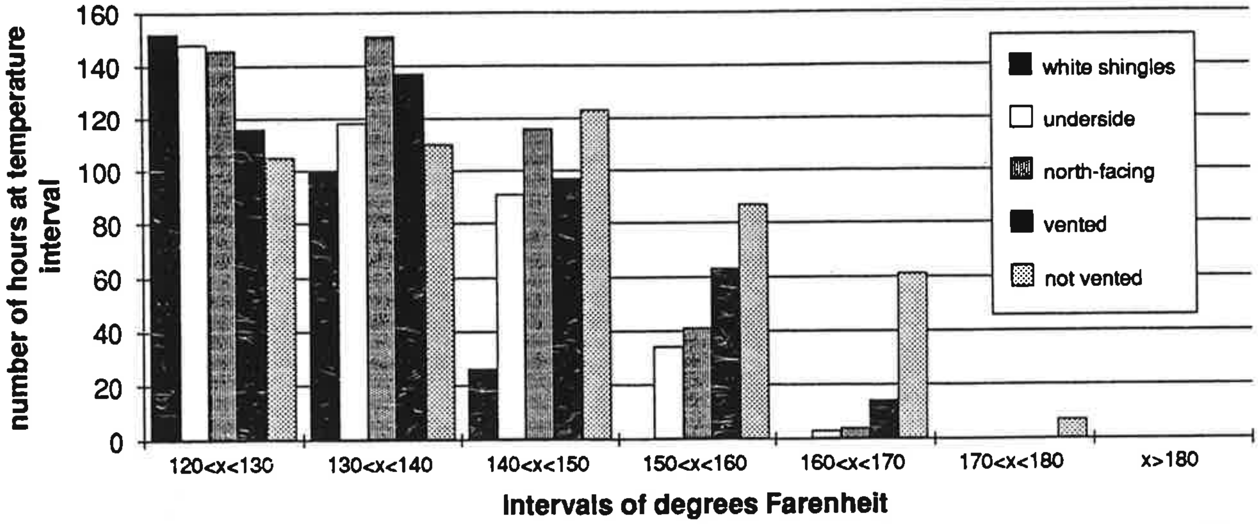


Figure 7 *Distribution of sheathing temperatures above 120°F for flat-ceiling attics during summer 1991.*

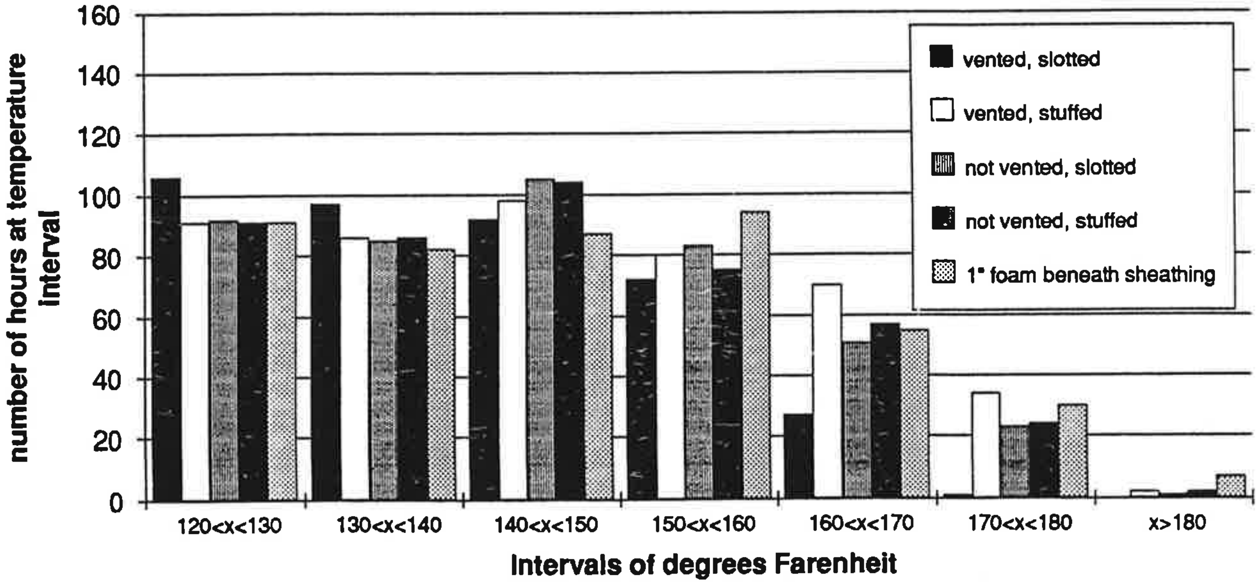


Figure 8 *Distribution of sheathing temperatures above 120°F for cathedral ceiling assemblies during summer 1991.*

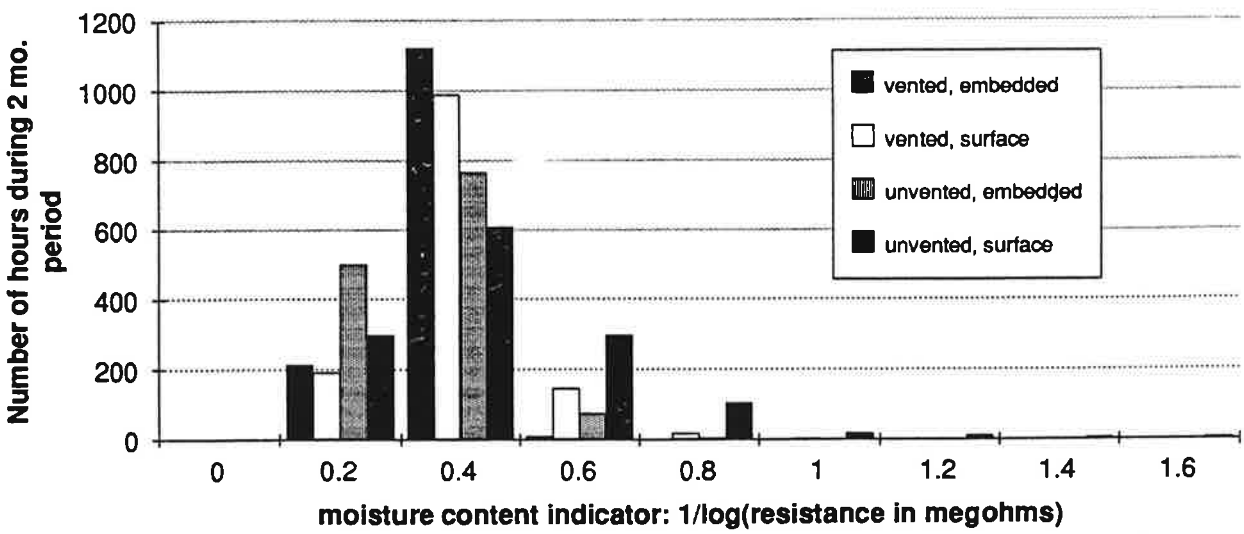


Figure 9 *Moisture conditions in flat-ceiling bays during the first winter (Jan-Feb 1991). A value of 0.4 corresponds to 13% mc: a value of 1.0 corresponds to 18% mc.*

The ceilings in the flat-ceiling bays were tested as very airtight, with no measurable leakage area (CMHC 1991). Pipes were installed as described in Table 1 and Figure 3, which, if uncapped, permit airflow under natural conditions. Throughout both winters of study, the pipes in the flat ceiling bays remained capped, with the exception of a two-week period at the end of February in the first winter. During that period, the weather was mild and there was no noticeable fluctuation in any of the flat-ceiling moisture content measurements.

In general, throughout both winters, the flat-ceiling attics showed no accumulation of moisture above 22%. With airtight ceilings, there was little difference in moisture performance among the vented and unvented bays.

Moisture Content: Cathedral Ceilings

In contrast to the flat-ceiling attics, the cathedral ceiling cavities showed a marked moisture response to winter conditions. In this analysis, only the north-facing slopes of the cathedral ceilings are considered, as the south-facing slopes showed dry conditions throughout both winters.

Data are available for only February of the first winter. On February 15, all of the ceiling holes were uncapped. Only one sensor location showed a marked response to the opening, i.e., the location in the vented, stuffed cavity that is uphill from the opening (between the ceiling opening and the ridge vent). The response of that cavity is shown in Figure 11.

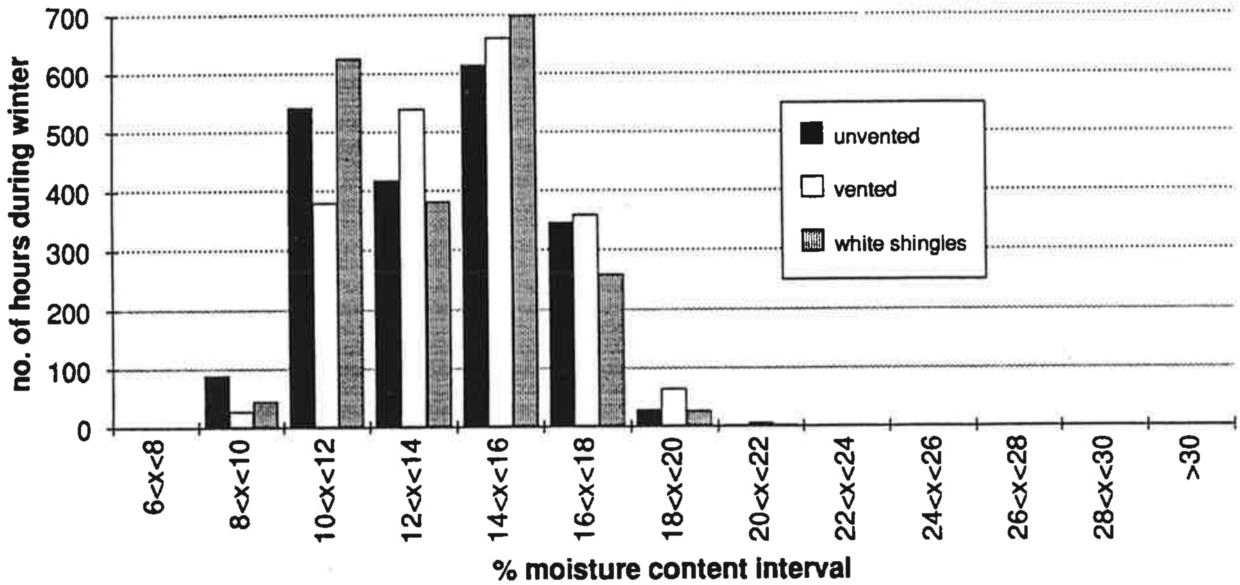


Figure 10 Moisture content distribution for the second winter, using % moisture content values.

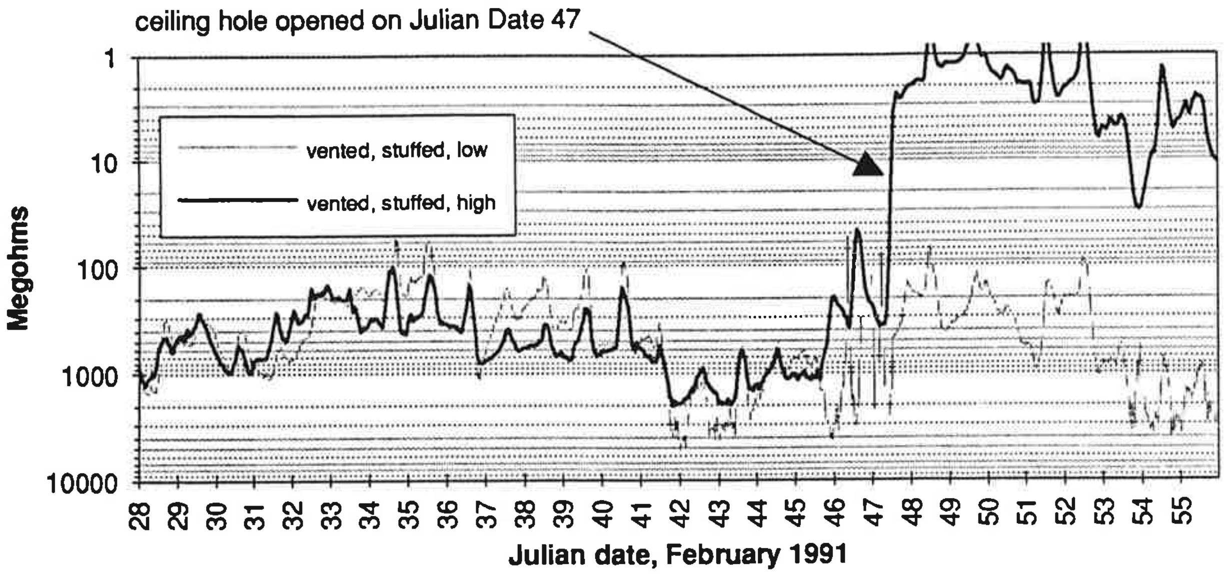


Figure 11 Resistance of moisture content probes in the vented/stuffed cavity during February 1991, showing increase in moisture content in the high sensor when the ceiling opening was uncapped.

Figure 12 shows the averages of the moisture content indicators (1/log[resistance]) for February 1991. It is apparent that the unvented cathedral ceiling cavities were significantly wetter than the vented cavities, with the exception mentioned above. The apparent reduction in moisture content in the cathedral/unvented/slotted case following the opening of the ceiling holes can be explained, at present, only as a result of the warmer outdoor temperatures that occurred following the opening of the ceiling holes. However, this explanation is weak in view of those other cases in which no change in moisture content occurred.

For the second winter (December 1991 through February 1992), the holes in the cathedral ceilings were kept open, permitting airflow through the ceiling plane. Figure 13 shows the average and maximum moisture contents measured using meters that permitted storing data as moisture content. The results from the second winter bear some similarity to the results from the previous winter—the vented/stuffed/high condition is once again subject to high moisture contents, and the unvented cavities are, in general, wetter than the vented cavities. The chart shows that the conditions unvented/slotted and vented/stuffed/high were subject to wood saturation conditions. These same results can be seen in Figure 14, a data distribution plot of the cathedral moisture content data for cathedral ceilings, in which the high and low sensor locations are combined. It is clear that the vented/slotted condition maintains the driest conditions during the winter when an opening in the ceiling is present.

DISCUSSION

The temperature findings indicate that ventilation does keep the attic volume cooler and that the reduced attic temperature has a cooling effect upon the sheathing. It has not been the purpose of this research to estimate the impact of these temperatures on the effective service life of roofing and sheathing materials nor the impact on the cooling load of a building. It is hoped that these data will assist any future efforts to quantify these effects.

The moisture content findings do not form a complete set of conditions. Further research is necessary to determine with greater confidence the effect of ceiling openings in flat-ceiling attics and the effect of closed ceilings in cathedral assemblies.

The performance of flat ceiling bays and cathedral ceiling bays is not identical. In flat ceiling bays, temperatures and moisture contents are more moderate than in cathedral ceilings. This is likely due to the fact that a single volume that faces both north and south sides is not subject to the extremes of temperature and vapor pressure present in isolated cavities. The traditional case of attic construction, with venting and with provision for airflow along the underside of the sheathing, showed satisfactory performance, even with a small hole in the ceiling.

There has been no physical deterioration of the attic sheathing in the flat ceiling attics, other than signs of rusting on the nail points, which has occurred in all of the attics. The cathedral ceilings have not been disassembled for visual inspection of the sheathing condition.

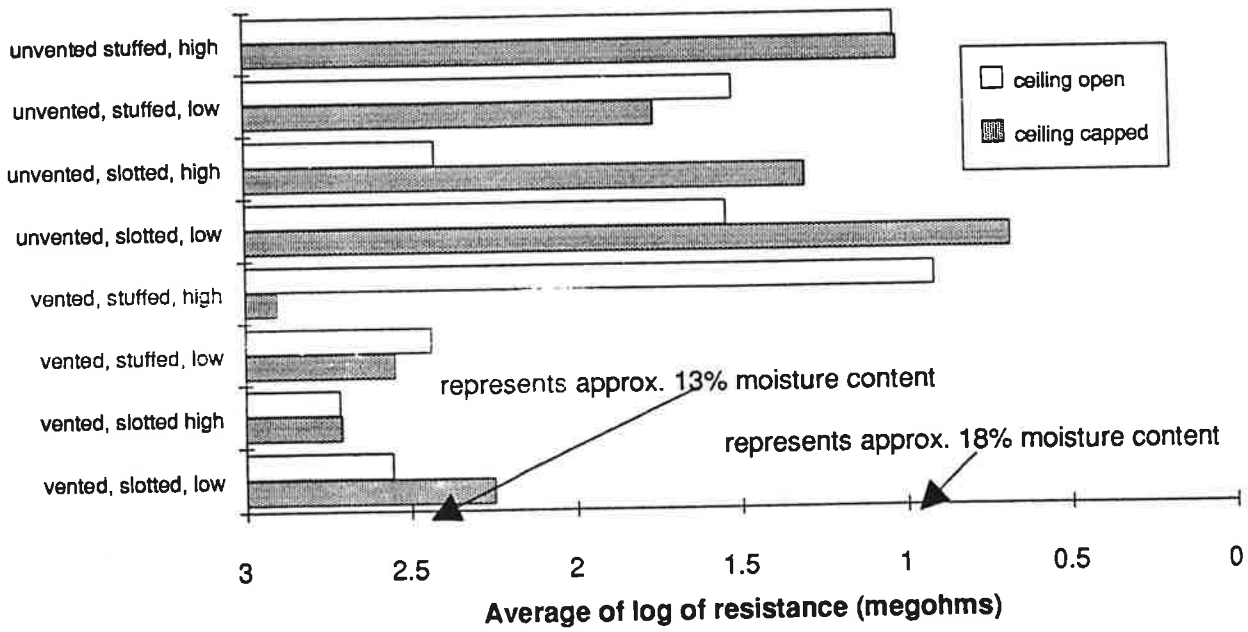


Figure 12 Average log (resistance) corresponding to moisture content in the cathedral ceilings during the first winter (Feb 1991).

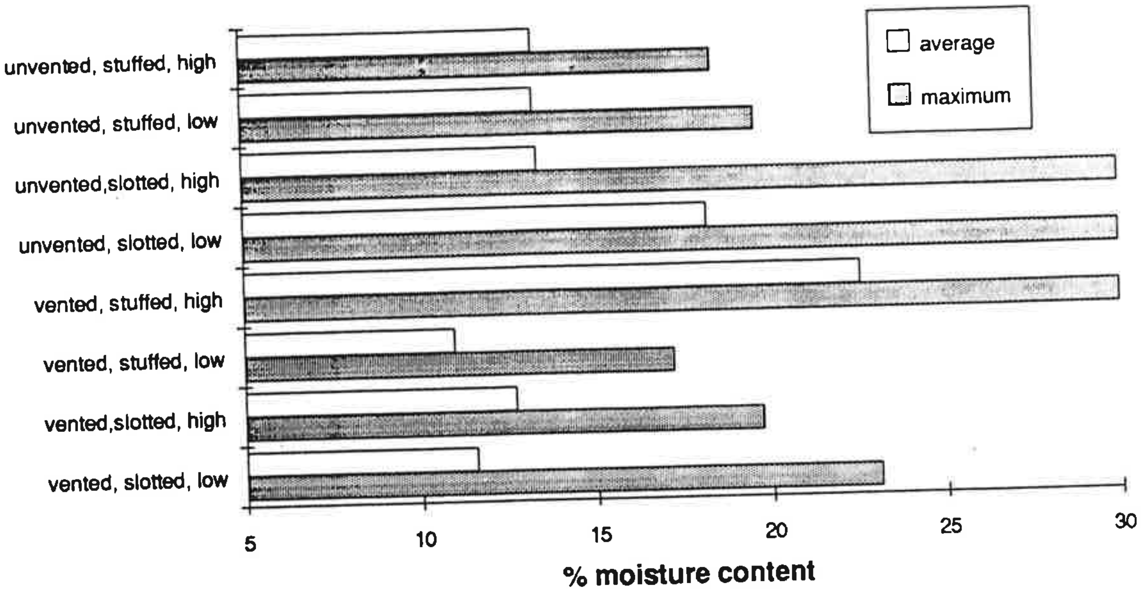


Figure 13 *Average and maximum moisture content in cathedral ceiling cavities during second winter. Ceiling openings were uncapped (open).*

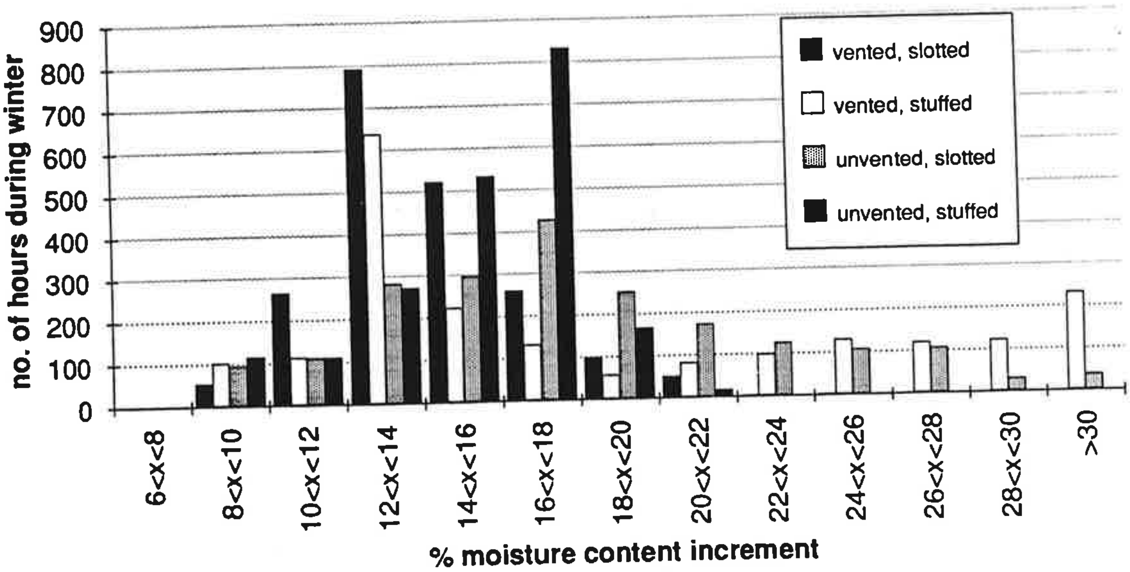


Figure 14 *Distribution curve of moisture contents during second winter.*

CONCLUSIONS

The maximum temperatures and the temperature distributions in comparable ventilated and unventilated attic spaces under certain field conditions have been demonstrated. The results show clearly that ventilation keeps attics cooler.

When flat ceilings and cathedral ceilings are constructed with venting and a continuous slot permitting airflow, both the temperatures and the moisture contents remain in a moderate range. This appears to hold true even with a small opening in the ceiling.

Flat-ceiling attics with no ceiling penetration showed little difference in moisture content performance whether vented or not vented.

Cathedral ceilings with ceiling penetrations showed significant moisture effects. While the unvented cathedral ceilings showed overall higher moisture contents than did the vented, care must be taken to avoid the condition seen in the vented/stuffed/high configuration when a ceiling opening is created.

Future work, modeling of attic effects in particular, will permit these results to be applied to other conditions of climate, orientation, and construction.

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