Measured Summer Values of Sheathing and Shingle Temperatures for Residential Attics and Cathedral Ceilings

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ABSTRACT

A research facility with several test cells was constructed in the Midwest. The facility contains roof assemblies with several variables:

- *flat-ceiling truss-framed attics and cathedral ceilings,*
- *dark and white shingles,*
- *vented and unvented construction,*
- *one- and two-layer shingle placement,*
- *measurement location toward the ridge and toward the eaves, and*
- roof deck installed directly over foam insulation.

Thermocouples are used to measure temperature hourly at various shingle layers—north and south side. Three summers of temperature data are used in this analysis and presented.

The temperature profiles for each condition are compared to a base case. By using regression of the test case against the base case, adjusted for a crossing point, the resulting regression slopes can legitimately describe a percent by which the test case is hotter or colder than the base case. Those data are presented and they permit a ranking of the various factors that affect shingle and roof sheathing temperature. An error analysis accompanies the comparison presentation.

The findings are used to sponsor a discussion of the role of ventilation as a temperature regulator for roof assemblies vis-a-vis the other factors that affect temperature. The implications of that ranking on the continued use of ventilation regulations in building codes and product warranties are discussed.

INTRODUCTION

This research is part of the Attic Performance Project, which seeks to characterize the heat and moisture performance of typical residential attic constructions. Since the late 1940s a centerpiece of regulated construction of attics has been the 1/300 ratio of vent net free area to horizontally projected roof area. First mention of attic ventilation as a performance factor appeared in literature of the Forest Products Laboratory regarding paint peeling (Browne 1933; Teesdale 1937). The recommendation for attic ventilation arose first in the literature of architectural practice by Rogers (1938). A year later, results of research on attic ventilation effects were published by Rowley et al. (1939). The 1/300 ratio appeared in a January 1942 Minimum Property Standards of the FHA. Research by Britton (1947) of HHFA in 1947 to 1949 used 1/300. Model building codes were introduced in 1948 to 1950 and typically included requirements for attic ventilation. Recollections of several persons in the roofing industry indicate that asphalt shingle warranties began to include a requirement for 1/300 venting in the 1960s. It is clear at least that literature on attic venting in the 1940s and 1950s does not address the effect of attic temperatures on roofing products.

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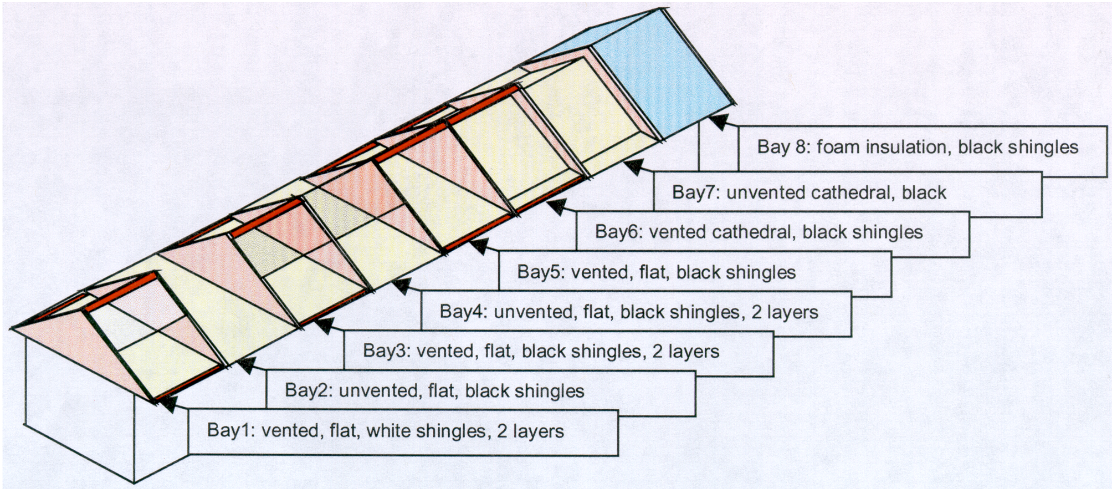

Figure 1 *Layout of study bays.*

Terrenzio et al. (1997) noted that asphalt shingle aging occurs from oxidation and volatilization, both of which are temperature-dependent. However, the research to date has not settled many of the questions regarding the link between temperature and shingle service life. The *1997 ASHRAE Handbook—Fundamentals* states "Ventilation may slightly reduce the temperature of shingles on a sloped roof, but it is not clear whether this slight difference is a significant factor in shortening the service life of shingles." This research seeks to address the first part of this Handbook claim by presenting measured data.

This research can be used in validation of building envelope models. Roof temperature models have been developed and used successfully (Wilkes; TenWolde; Burch). It should also be seen in comparison with other reports of measured temperatures (Parker 1998; Rudd 1998; Winandy et al. 2000). It is hoped that the method of comparison provided here represents an improvement in the means of representing measured data.

This research presents the temperatures of shingles and sheathing in different steep roof assemblies as a function of ventilation, shingle color, orientation, framing type, number of layers of shingles, and insulation placement. It does not present data on roof systems in locations other than the field study site, nor for roof systems other than the 5:12 pitch residential-style roof assemblies that were monitored.

The aim of this work is to provide a simple representation that can be used to estimate the temperature consequences of various design decisions.

SETUP

The building is located in Champaign, Ill., at 40ºN latitude. The prevailing winds are from the west. The study building was completed in 1990. Indoor temperatures were maintained at 75ºF during the summer. The orientation of the ridge is east-west. The pitch of the roof is 5:12. The roof sheathing material is oriented strand board (7/16 in.). There is #15 asphalt felt placed between the sheathing and the shingle roof.

Thermal insulation is used to isolate the attic areas from one another. The trusses separating bays are insulated with high-density fiberglass in the plane of the truss and foil-faced polyisocyanurate insulation applied at the face of the truss. Polyisocyanurate board insulation is applied to the rafters that separate cathedral ceiling bays.

Roof Framing

Five of the eight framing cases (bays 1 through 5) are framed with roof trusses, providing a flat ceiling. The R-30 fiberglass insulation is placed on top of the drywall ceiling. Three of the bays (6 through 8) are of cathedral ceiling construction. In bays 6 and 7, nominal 10 in. R-30 fiberglass batt insulation with kraft facing is fastened at the bottom of the 2×12 framing cavity. The resulting airspace between the top of the batt and the underside of the sheathing was not controlled to a uniform dimension. There were no air chutes in the cathedral ceilings. Bay 8 contains 1 in. of foil-faced polyisocyanurate insulation directly beneath the sheathing, with R-30 fiberglass insulation immediately beneath (see Figure 1).

Two pairs of bays have somewhat the same conditions. Bays 3 and 5 are flat-ceiling truss-framed vented bays with dark shingles. Bays 2 and 4 have flat ceilings and dark shingles, but they are not vented. However, there are differences between these bays that would affect the measured performance.

- Bay 5 is next to a cathedral ceiling bay, separated by a gable wall, insulated with 1 in. of foil-faced polyisocyanurate and 1.5 in. of fiberglass insulation. During summer, it is expected that heat transfer may occur between the conditioned space of bay 6 and the unconditioned space of bay 6.

- Bays 3 and 4 have a second layer of shingles over the top half of the roof. Bays 2 and 5 do not.
- Bays 4 and 5 were rewired between the summers of 1994 and 1995. The cabling appears to be correct but anomalies in the data (presented below) were not pursued.

Although not shown in Figure 1 for the purpose of simplicity, there are conditioned bays at the east and west ends of the building to ensure that bays 1 and 8 are not exposed to the exterior at their ends.

Vented/Unvented

Vented roofs have ridge and soffit vents and continuous air passages between the vents. The nominal vent ratio of these bays is 1/150 (ratio of the total nominal net free area of the vent over the projected horizontal roof area). The condition of the vent slot is described above. In bay 8 (unvented), foil-faced polyisocyanurate insulation (1 in.) is placed directly against the underside of the sheathing, with R-30 fiberglass insulation beneath that. "Unvented" roofs have cap shingles at the ridge and vinyl soffit components without perforations.

Bays 1, 3, 5, and 6 are vented.

Ridge/Eaves

The roof has two slopes, each with a projected length of 12 ft—10 ft over conditioned space and 2 ft of overhang—and an actual length of 13 ft. Sensors are located 3 ft down from the ridge and 3 ft up from the plate.

White Shingles/Dark Shingles

Bay 1 is covered with white colored shingles. The other bays are covered with dark shingles. The roof contains shingles with both fiberglass and organic reinforcement. The shingles were installed in 1989.

The shingles described as "dark" contain areas covered with gray granules and areas covered with black granules. The individual thermocouples could be located under either gray areas or black areas. Solar absorptivity was measured using full solar-spectrum radiometers positioned in the plane of the roof facing skyward and roof-ward, and the measured absorptivity of the dark shingles represents an average of the gray areas and the black areas. The dark shingle absorptivity was measured at 0.94; the white shingle absorptivity was 0.77.

Layers of Shingles

In 1993, a second layer of shingles was added to the single layer of shingles at the upper half of the roofs of bays 1 (white shingles, vented), 3 (dark shingles vented), and 4 (dark shingles, unvented). Thermocouples were placed as shown in Figure 2 to measure temperature at the surface between the upper and lower shingle material in those three bays. Bays 1, 3, and 4 are the only bays where shingle temperatures were measured.

Instrumentation

Surface temperature was measured with 24ga thermocouples with lengths between 12 ft and 20 ft. The reference junction temperature was measured with a reference thermistor. Air temperatures were measured using 100 ohm PRT probes with radiant protection at a level 3 in. beneath the underside of the roof sheathing. Data were collected at hourly intervals using scientific data logging equipment. The hourly measurements represent an average of four measurements taken during the hour interval.

The data in this report represent measurements taken from June 1 to August 31 of years 1994, 1995, and 1996. In subsequent years, equipment problems led to more incomplete data sets, so those data are not included here. Data relating to bays 4 and 5 represent measurements taken in 1995 and 1996, as these two bays had a different configuration in 1994. The data from bays 4 and 5 from 1995 and 1996 present some anomalies, though a check of cabling indicate it is intact and correct, and the later data are consistent with the data from 1995 and 1996. Data from two measurement sites in bay 1 do have cabling problems. The data from those sites are clearly anomalous beginning in 1995, and those data have been excluded.

Occasional temperature measurements of the exterior surface of the shingles were made using a hand-held infrared pyrometer. The precision of these measurements was approximately 1ºC, wider than the precision of the thermocouple measurements reported here. During sunny periods, the readings fluctuated by several ºC. The surface measurements during sunny days for upwind locations were cooler than downwind conditions by several degrees.

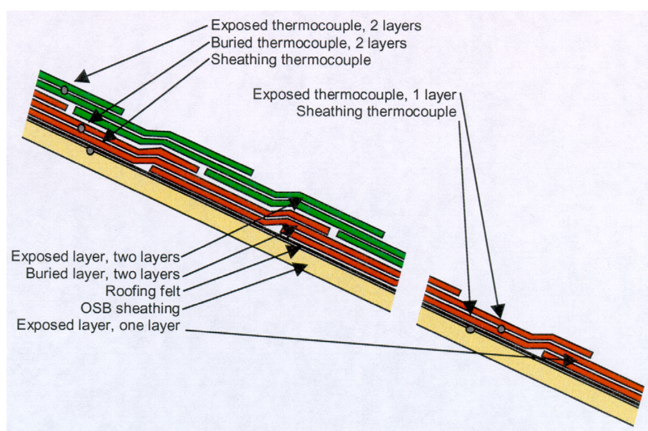

Figure 2 *Schematic diagram showing shingles and thermocouple placement, bays 1, 3, and 4. Note that the thermocouple placement called "sheathing" represents the top of the sheathing as well as the underside of the felt. The "sheathing" location represents the sheathing/roof material interface.*

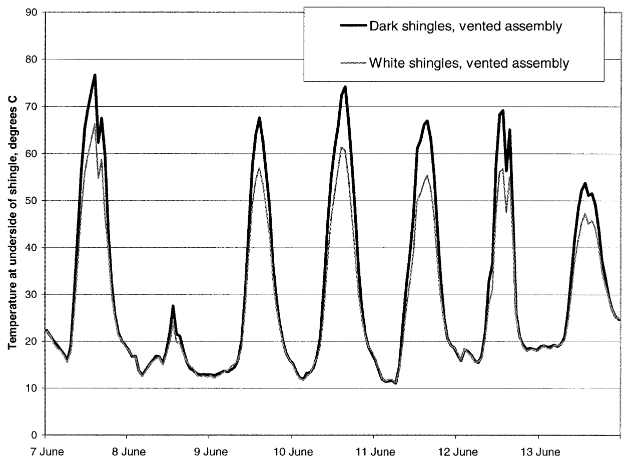

Figure 3 *Sample measured temperature data for two conditions: (1) underside of dark shingles, ventilated attic, and (2) underside of white shingles, ventilated attic.*

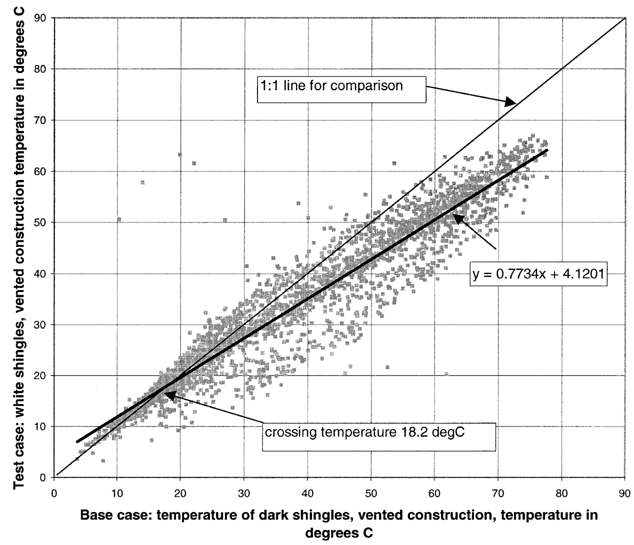

Figure 4 *Illustration of linear regression method that uses comparison of test case values against a base case. In this example, the temperature at the underside of white shingles (vented attic) is compared to the temperature at the underside of dark shingles (vented attic). The slope of the regression line is 0.773, so the white shingles are 22.7% cooler (1-.773).*

FINDINGS

Data Representation

It is not a trivial matter to determine the best representation of temperature data for purposes of comparison of building assemblies. There does not appear to be literature on the correlation between shingle temperature and shingle performance, which might suggest a preferred method of representing measured values of temperature of roof components. Several representations are possible (e.g., maximum temperature, number of hours above a threshold, hourly bin values, exceedence of a threshold, etc.), but none of these approaches is favored in the absence of an accepted mechanism for failure.

The data representation in this report seeks to answer questions that may be phrased as "How much hotter is condition A compared to condition B?" In this report, there is a single "base case" for sheathing (bay 3, flat-ceiling construction, soffit and ridge ventilation, south side, dark shingles, toward the eaves, one layer of shingles) and another base case for shingles (same conditions as for sheathing, but temperature measured at the interface between mated shingles.) All other conditions are compared to either the sheathing base case or the shingle base case.

Figure 3 shows sample sheathing temperature data taken during summertime 1994 for two conditions—one the base case and another, the unvented cathedral ceiling (foam insulation) case. What is evident is higher temperatures during the day and lower temperatures at night for the unvented cathedral ceiling.

Figure 4 is a graphical representation of how the data comparison was done, using the same two datasets as base case and comparison case. The higher daytime temperatures and lower nighttime temperatures are evident in the comparison.

There are no standard methods for conducting a comparison such as this. The reason for selecting this procedure is that it makes no presumptions about which temperatures may be important; rather, it allows all the temperatures for any condition to be produced, given known temperatures for the base case, and given the error shown in Tables 1 and 2.

The temperature comparison for all cases (except the base case) is achieved as follows:

- Do a linear regression of the simultaneous values of the comparison case and base case.
- Use a slope comparison that has a floating offset; use the slope comparison to directly indicate the percent temperature difference between the comparison and base cases.
- Calculate the intercept ($T_{intercept}$) of the comparison and base data sets; determine the "crossing" temperature where the regression line crosses the $y = x$ line. $T_{cross} = T_{intercept}/(1\text{-slope})$.
- Calculate the standard error of the y-estimate, in the same units as the data, degrees K.

The temperature comparison is shown as a percentage, with positive values indicating "hotter than" and negative values indicating "colder than" the base case. If temperatures of the base case are known, then values of all the other conditions can be estimated from the slope, intercept (or crossing) values, and the error can be estimated from the standard error.

TABLE 1
Comparison of Cases to Base Case (in Bold) and Test Case Temperatures, Measured at Top of the Sheathing (at the Interface Between the Sheathing and the Roofing Materials)

	Vented bays				Unvented bays			
	Bay 1							
White; flat ceiling truss frame	vented	vented	vented	vented				
Orientation	north	north	south	south				
Location	eaves	ridge	ridge	eaves				
cooler (-) hotter (+)	-30.0%	-32.4%	-22.1%*	-20.0%*				
crossing (ºC)	20.4	21.6	19.7	18.0				
Standard error of the estimate (K)	4.8	5.6	2.1	1.1				
	Bay 3				Bay 2			
Dark, flat ceiling truss frame	vented	vented	vented	**vented**	no vent	no vent	no vent	no vent
Orientation	north	north	south	**south**	north	north	south	south
Location	eaves	ridge	ridge	**eaves**	eaves	ridge	ridge	eaves
cooler (-) hotter (+)	-8.7%	-10.8%	-0.7%	**Base case**	-4.2%	-2.3%	7.6%	9.7%
crossing (ºC)	27.1	30.7	125.8***		35.1	51.7***	17.1	21.3
Standard error of the estimate (K)	3.1	3.5	2.6		2.9	2.8	1.2	0.7
	Bay 5				Bay 4			
Dark, flat ceiling truss frame*	vented	vented	vented	vented	no vent	no vent	no vent	no vent
Orientation	north	north	south	south	north	north	south	south
Location	eaves	ridge	ridge	eaves	eaves	ridge	ridge	eaves
cooler (-) hotter (+)	-10.0%**	-4.7%**	3.4%**	-4.7%**	-4.2%**	-8.1%**	-0.8%**	7.5%**
crossing (ºC)	27.0	37.3	13.6	23.1	40.5	38.6	184.3***	17.9
Standard error of the estimate (K)	2.8	2.9	0.8	0.7	2.5	3.4	2.5	0.6
	Bay 6				Bay 7			
Dark; cathedral ceiling	vented	vented	vented	vented	no vent	no vent	no vent	no vent
Orientation	north	north	south	south	north	north	south	south
Location	eaves	ridge	ridge	eaves	eaves	ridge	ridge	eaves
cooler (-) hotter (+)	-8.8%	0.7%	14.5%	-15.3%	2.4%	4.8%	18.7%	17.7%
crossing (ºC)	13.2	95.6***	28.2	13.7	45.4	28.0	25.5	26.4
Standard error of the estimate (K)	4.2	4.3	3.2	3.5	3.9	4.0	3.1	3.1
					Bay 8			
Dark; cathedral ceiling with 1" polyiso foam beneath deck					no vent	no vent	no vent	no vent
Orientation					north	north	south	south
Location					eaves	ridge	ridge	eaves
cooler (-) hotter (+)					5.5%	7.7%	23.3%	23.1%
crossing (ºC)					33.2	27.5	25.7	26.6
Standard error of the estimate (K)					3.8	4.2	3.3	3.3

* 1994 data only. See text.
** 1995-1996 data only. See text.
***Where the temperature difference between base and test case is small, and the slope lines are almost parallel, less significance is attached to the crossing temperature.

TABLE 2
Shingle Temperatures Compared to Base Case (Shown in Bold)
Summer Data, Two Years

	Bay 1					
Shingles	white	white	white	white	white	white
Vented	yes	yes	yes	yes	yes	yes
Orientation	north	north	south	south	north	south
roof location	eave	ridge	ridge	eave	ridge	ridge
Layers	1	2	2	1	2	2
exposed/buried	exposed	buried	buried	exposed	exposed	exposed
cooler (-) hotter (+)	-32.0%	-34.3%	-23.4%	-22.7%	-38.0%	-27.2%
crossing (ºC)	20.5	21.4	19.6	18.2	22.2	21.0
St. Error of estimate (K)	3.6	3.9	3.6	3.3	4.2	4.0
	Bay 3					
Shingles	dark	dark	dark	**dark**	dark	dark
Vented	yes	yes	yes	**yes**	yes	yes
Orientation	north	north	south	**south**	north	south
roof location	eave	ridge	ridge	**eave**	ridge	ridge
Layers	1	2	2	**1**	2	2
exposed/buried	exposed	buried	buried	**exposed**	exposed	exposed
cooler (-) hotter (+)	-14.9%	-14.5%	-4.3%	**Base case**	-11.1%	3.0%
crossing (ºC)	25.4	29.5	38.5		29.5	12.9
St. Error of estimate (K)	2.7	3.5	2.4		3.1	2.4
	Bay 4					
shingles	dark	dark	dark	dark	dark	dark
vented	no	no	no	no	no	no
orientation	north	north	south	south	north	south
roof location	eave	ridge	ridge	eave	ridge	ridge
layers	1	2	2	1	2	2
exposed/buried	exposed	buried	buried	exposed	exposed	exposed
cooler (-) hotter (+)	-12.5%	-14.3%	0.0%	2.7%	-9.0%	4.7%
crossing (ºC)	28.5	30.6		13.8	32.7	13.0
St. Error of estimate (K)	3.0	3.8	2.3	1.0	3.2	1.2

The "crossing" approach is used because it applies more intuitively than the *y*-intercept from which it is derived. For most of the conditions, the crossing value is between 10ºC and 40ºC. As the slope of the test case approaches 1,000, the significance of the crossing temperature diminishes. (If the slope of the test case were 1,000, there would be no crossing value, as the slope of the test case and base case would be identical and parallel). If the crossing value were, for example, 18ºC, then at temperatures above or below 18ºC, the comparison case will be hotter or colder than the base case by the percent amount, while at 18ºC, the two cases will have the same temperature. Briefly, if unknown condition A is "*x*(%)hotter" than known condition B, then

$$(T_A - T_{cross}) / (T_B - T_{cross}) = (1+x) \quad \text{or}$$

$$T_A = T_{cross} + (1+x) * (T_B - T_{cross}),$$

where *T* represents the temperature at A, B, or crossing.

As an example, Table 2 shows that the base case (Bay 3, vented, toward the eaves, dark shingles) compares to the Bay 1 test case (vented, toward the eaves, white shingles) as follows:

- % hotter: –22.7% (i.e., 22.7% cooler)
- crossing temperature: 18.2ºC
- standard error of the estimate: 3.3 K

If the temperature of the base case (dark) is 80ºC, then the temperature of the test case (white) is

$$18.2 + (0.773)*(80-18.2) = 58\ (ºC).$$

The reliability of this estimate is seen in the standard error of the estimate, 3.3 K. The standard error of the estimate is closely related to the standard deviation of the residuals (the difference between the base case and test case values at an point).

This representation of the data is a form of correlational analysis (i.e., a one-dimensional linear regression of simultaneous time series data). However, crossing temperatures are used rather than y-intercept in the hope that crossing temperature would be more intuitively significant. In the past the lag time among data sets has been analyzed. It was determined (but not published) that the lag time of a solar signal through the mass of material in the roof assemblies (from shingles to ceiling) of the test bays was one hour or less. Thus, lag time and spectral analysis of the data are not included in this analysis. Derivation of temperature data from outdoor conditionsis not presented here. To do so would be to introduce additional imprecision and inaccuracy with the inclusion of measured conditions of outdoor temperature, solar insolation, wind speed and direction, rain fall, etc. Regressions other than linear are not attempted here. The linearity seen in Figure 4 is representative of the linearity of other comparisons.

SHEATHING CONDITIONS

Flat-Ceiling Attics

Recall that the "sheathing" temperature in this study relates to the temperature taken at the top of the sheathing (i.e., at the interface between the sheathing and the roofing material). Several findings regarding the sheathing temperature measurements appear from a review of Table 1.

- The north side sheathing is cooler than the south side among all of the flat-ceiling bays.
- The sheathing of attic assemblies with white roofs is considerably cooler than the sheathing of dark-roofed assemblies. The south-side temperatures are 22% and 20% cooler than the base case. (Data from 1994 only are used for the white shingle/dark shingle comparisons, due to equipment difficulties beginning 1995 at the two south-side white shingle locations.)
- A comparison of bays 2 and 3 shows venting to have a cooling effect of 7.6% and 9.7% on the top side of the sheathing. Bays 4 and 5 were rewired in 1995 and the rewired locations show anomalous performance. They are reported here but with concern for their use. The most peculiar anomaly consists of slightly higher temperatures toward the ridge on the south side in the vented bay compared to the unvented bay.

Cathedral Ceiling Construction

The two unvented cathedral ceiling bays, 7 and 8, show elevated temperatures. With fiberglass insulation, the sheathing of bay 7 shows a temperature elevation of about 18% while with polyisocyanurate insulation plus fiberglass insulation, the sheathing temperature is elevated above the base case by about 23%. There is no strong thermal gradient along the unvented cathedral ceiling roof.

Bay 6, the vented cathedral-framed bay, shows a very strong sheathing temperature gradient from eaves to the ridge, about 15% colder than the base case at the eaves and 15% hotter than the base case toward the ridge. The thermal pumping action that produces such a strong gradient is not difficult to imagine. It becomes apparent that venting can cool the lower section of a vented cathedral ceiling quite effectively, but the cooling effect is greatly reduced for the upper part of the cavity.

Shingle Temperatures

Table 2 represents the comparison temperatures taken at the underside of the shingles. Several effects can be seen.

- In a comparison of the south side eave condition, with one thickness of shingles, the temperature of white shingles is about 23% lower compared to the temperature of dark shingles.
- In a comparison of temperatures with different layers of shingles, the buried shingles are cooler than the exposed shingles. The exposed dark shingles of the double layer on the south side are slightly warmer (3%) than the exposed shingles of just one layer. However, the exposed white shingle of the double layer is cooler than the exposed single-layer white shingle (27.2% cooler compared to 22.7% cooler).
- In a comparison of vented v. unvented conditions, the unvented condition shingle corresponding to the base case is 2.7% hotter. In a comparison of the exposed shingles in two-layer construction, the unvented condition is 4.7% hotter than the base case while the vented condition is 3.0% hotter.

CONCLUSIONS

Hourly temperature values have been measured in roof sheathing and shingles in several typical residential roof assemblies at a test facility under field conditions. The data have been represented using linear regression of individual cases against a base case (dark shingles, south side, vented assembly, flat-ceiling framing, toward the eaves). The slope of the regression line permits the temperature of the comparison case to be expressed as "hotter than" or "colder than" the base case as a percent. Data are shown for three years for most sheathing conditions and for two years for the shingle conditions. Data anomalies have been recognized and are indicated.

The cooling effect of ventilation on the upper side of sheathing was 9.7% in the most direct comparison (at the eave, south side) and similar for the ridge south side condition. The cooling effect of white shingles was 20% in the most direct comparison (at the eave) and similar for the ridge. These findings are from three years of data in bays 2 and 3. In a smaller data set of bays 4 and 5, the findings require further study.

Unvented cathedral ceiling construction is hotter than flat-ceiling construction. With fiberglass insulation only, the unvented sheathing is 17.7% hotter (eaves) and 18.7% hotter (ridge). With foil faced foam insulation directly beneath the sheathing, the sheathing temperature is 23.1% (eaves) and 23.3% hotter (ridge). There is a strong temperature gradient in the sheathing on the south side of the vented cathedral ceiling. At a point 3 ft up from the wall plate (“eaves”), the sheathing temperature is 15.3% cooler than the base case; at a point 3 ft down from the ridge, the sheathing temperature is 14.5% hotter than the base case.

The cooling effect of ventilation on shingles is 2.7% in the base case comparison. The cooling effect of ventilation on two layers of shingles is similar. The reduction in shingle temperature attributable to color is 22.7% in the most comparable case and similar for other cases. The heating effect of two layers of shingles is 3.0% on the exposed dark shingle, though the exposed white shingle of two-layer construction is cooler than the exposed shingle of single-layer construction.

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