Analysis of three-year Wisconsin temperature histories for roof systems using wood, wood-thermoplastic composite, and fiberglass shingles

Jerrold E. Winandy*
Cherilyn A. Hatfield

Abstract

Temperature histories for various types of roof shingles, wood roof sheathing, rafters, and nonventilated attics were monitored in outdoor attic structures using simulated North American light-framed construction. In this paper, 3-year thermal load histories for wood-based composite roof sheathing, wood rafters, and attics under western redcedar (WRC) shingles, wood-thermoplastic composite (WTPC) shingles, and black and white fiberglass shingles are reported and analyzed. The maximum hourly-average temperatures experienced were 70.7 °C and 61.8 °C for black and white fiberglass shingles, respectively; 48.2 °C for WRC shingles; and 45.7 °C and 46.3 °C for WTPC shingles applied over lath or directly over felt, respectively. On hot summer days, black fiberglass shingles were commonly found to be almost 10 °C hotter than white fiberglass shingles and more than 20 °C hotter than WRC or WTPC shingles. Other components in the roof assemblies and the attic air temperatures followed similar trends. The implications of these thermal loads under different types of roof shingles on comparative service-life for the shingles and the various wood components in the roof systems are discussed.

Until recently, our understanding of thermal loads experienced by roof systems in North American light-framed construction was limited. Knowing these thermal loads is critical to modeling the long-term serviceability of these roof systems. Few reliable data were available on actual thermal loads for individual wood and wood composite components as we build homes today in North America (i.e., materials and construction practices). Thus, we were unable to specifically correlate experiments using steady-state laboratory exposure with field exposures to diurnal and seasonal temperature cycles.

Roof system temperature histories for wood and wood-composite components of roof systems using fiberglass shingles are now available for 8 years of exposure in Madison, Wisconsin (43°N latitude) and 4 years of exposure in Starkville, Mississippi (33°N latitude) (Winandy and Beaumont 1995, Winandy et al. 2000). Summer temperatures of five different shingle materials and associated attic temperatures were reported by Winandy et al. (2004). More recently, summary roof temperature data, but without systematic analysis, were presented for calendar years 2003, 2004 (Winandy et al. 2005), and 2005 (Winandy 2006). The overall program has involved multiple studies conducted over a 15-year period. Roof temperature data such as presented in this paper can be applied to predictive roof temperature models to make performance interpretations for other building designs. This particular project is part of a long-term field-monitoring program to define thermal loads on North American light-framed construction. It is also helping us understand the critical performance issues related to durability, thermal stability, and UV weathering for wood-thermoplastic roofing shingles.

Objective

The objective of the roof temperature assessment project was to document and analyze actual thermal load histories of various wood components and shingle materials as used in traditional North American light-framed construction. This paper summarizes findings from five papers (Winandy and

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The authors are, respectively, Project Leader and Statistician, USDA Forest Serv., Forest Products Lab., Madison, Wisconsin (jwinandy@fs.fed.us, cahatfield@fs.fed.us). This paper was received for publication in January 2007. Article No. 10268.
*Forest Products Society Member.

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Beaumont 1995; Winandy et al. 2000, 2004, 2005; Winandy 2006) detailing this 15-year roof temperature assessment project and compares 3-year roof temperature histories for new thermoplastic composite shingles to wood and fiberglass shingles exposed in southern Wisconsin. Thermal load histories are critical variables in assessing long-term service life of roof coverings and materials within the entire roof system. Thus, knowing thermal loads is critical to any subsequent modeling of the rate or rates of thermal degradation for roof shingles, wood composite sheathing, and rafter lumber (TenWolde 1997). Thermal load information can also provide valuable insight to the influence of individual roof-system components on potential energy costs for heating and cooling the structure.

Background

Heyer (1963) reported temperature histories for wall and roof systems for six houses and one office building for periods from 1 week to two consecutive summers (June to August). The houses were located in Arizona, Georgia, Oregon, Texas, and Wisconsin. In any 1 year, maximum roof temperatures were found to reach 75 °C, but the cumulative duration of temperatures over 70 °C did not exceed 21 hours; the cumulative duration of temperatures over 65 °C did not exceed 64 hours. Ozkan (1993) and Wilkes (1989) found temperatures of the surface and various components of flat roof systems under single-ply black rubber roofing to be as high as 93 °C.

Winandy et al. (2000) reported annual temperature histories from 1991 to 1999 in Wisconsin (WI) and from 1996 to 1999 in Mississippi (MS) for various wood components used in conventional North American roof assemblies under fiberglass shingles. Over the 4-year exposure in Mississippi, maximum "1-hour average" temperatures recorded for black-shingled roofs in dry structures were 78 °C and 63 °C for the top and bottom plies of the plywood roof sheathing, respectively, and 58 °C for the rafters. Maximum temperatures recorded for the matched WI structures were 75 °C, 59 °C, and 54 °C, respectively. They summarized these data by developing 8- or 4-year annualized temperature histories for each individual wood and wood composite component in the exposure structures. They found that the distributional forms of annualized data from the MS structures were slightly skewed by the longer summer in Mississippi, generally resulting in many more hours of high temperatures per year than for the matched WI structures. They also showed that MS and WI black-shingled structures experienced only small differences (3 to 4 °C) in maximum record temperatures. The researchers ascertained that daytime high temperatures at the top of the plywood roof sheathing were often controlled more by solar gain than by outside air or attic air temperatures. Similarly, temperatures at the bottom of the roof sheathing were usually controlled by solar gain, except on a few of the hottest days, when sheathing temperatures were strongly influenced by outside air or attic air temperatures. Rafter temperatures were partially influenced by thermal radiation from sheathing but usually controlled by attic air temperatures, except on a few of the hottest days, when they were more strongly influenced by solar radiation. Another major difference in the thermal histories of various wood and wood composite components used in attics in a northern exposure (Wisconsin) compared with those used in a southern exposure (Mississippi) was in minimum temperatures, which were as much as 20 °C lower in the WI structures.

Computer models have been developed that predict temperature and moisture content (MC) of wood composite roof sheathing and other lumber roof members based on various construction details, materials, ventilation factors, and solar gain (radiation load) for the roof (APA 1989, TenWolde 1997, Wilkes 1989). TenWolde (1997) developed and verified a predictive roof temperature model for sloped wood-based roof systems using data from a University of Illinois facility (Rose 1995). This model showed that the temperature of the exterior surfaces of plywood roof sheathing was dominated by solar gain and heat exchange between the surface and ambient air. Diurnal temperature variation and hourly sheathing temperature histories were also influenced by the radiant energy absorptivity of the roofing surface, by roof pitch, and to a lesser extent, by insulation and attic ventilation. An integrated approach to predicting exposure temperatures of various components in wood roof assemblies across North America was made possible by the TenWolde roof temperature model. It was used to predict roof temperature histories for plywood roof sheathing at a dozen locations across the United States to estimate engineering design adjustments for fire-retardant-treated plywood roof sheathing in ASTM Standard D 6305–02 (ASTM 2005a) and for fire-retardant-treated roof truss lumber in ASTM Standard D 6841–03 (ASTM 2005b).

Holton and Beggs (1997) studied two roof constructions, one with traditional dark-brown asphalt composition shingles and the other with a brown plastic roofing material. They found that attic air temperatures were approximately 11 °C cooler under plastic roofing on hot summer days (~33 °C). They did not monitor the temperatures of members of the wood roof assemblies.

Winandy et al. (2004, 2005, and Winandy 2006) monitored temperatures of various types of shingles and roof-system components. Temperatures of four types of shingles were monitored at the midpoint of their cross-sectional thickness. Summer temperatures were found to be much higher for black fiberglass shingles than for similar white fiberglass shingles. Western redcedar (WRC) and wood-thermoplastic composite (WTPC) shingles experienced similar internal temperatures but were cooler than either black or white fiberglass shingles. During a typical summer day, sheathing under fiberglass shingles was often hotter than the shingles themselves, probably as a result of a time lag between exposure and response. Sheathing temperatures under WTPC and WRC shingles were virtually the same but generally much cooler than temperatures under fiberglass shingles. Sheathing under WTPC shingles applied directly on lath was noticeably cooler than sheathing under WTPC shingles installed on felt over the sheathing.

Methods

Five field exposure structures were constructed in 1991 near Madison, Wisconsin (**Fig. 1**). They face south in a shadeless area open to direct sunlight and were spaced far enough apart to prevent any structure from shading an adjacent structure. Each was 3.7 m wide by 4.9 m long and constructed to simulate part of a typical attic-roof systems in a multifamily residential structure. Winandy and Beaumont (1995) described the construction of these structures in detail.

In the fall of 2001, the shingles and plywood sheathing were removed from one white-shingled and two black-shingled

Figure 1. — Exposure structures located at FPL test site near Madison, Wisconsin. All five units were similarly constructed except for roofing materials and were instrumented for long-term temperature monitoring of roof assemblies. Shown from the foreground are black fiberglass shingles, western redcedar shingles (being installed), wood-thermoplastic composite shingles (two structures—closer with lath, further without lath), and white fiberglass shingles.

structures at the Wisconsin site. These structures were resheathed with 12-mm-thick oriented strandboard (OSB) roof sheathing. The commercial OSB was made from aspen flakes and an isocyanate resin. One structure was then shingled with western redcedar (WRC) shingles directly over felt, and the other two structures were shingled with prototype wood-thermoplastic composite (WTPC) shingles (**Fig. 2**). The WTPC shingles were 0.86 m wide by 0.45 m high, made from a 50/45/5 blend of wood flour (40-mesh postindustrial scrap maple), high-density polyethylene (~80% recycled milk jug PE and ~20% virgin HDPE copolymer), and nearly 5 percent additives (~2% maleic anhydride-grafted coupling agent and ≤1% each pigment, fire-retardant, and UV- and heat-stabilizers). Each shingle was compression molded to have a wood-grained texture on the top (exposed) surface (**Fig. 3**) and a waffled surface on the bottom to reduce weight (**Fig. 2b**). In one WTPC construction, shingles were laid directly over felt, as were the WRC shingles. This type of application is usually considered to represent a worst-case scenario for shingle durability. In the other WTPC construction, shingles were laid over a horizontal course of 9-mm-thick lath that, in turn, was laid over a similar vertical course of lath.

In summer 2002, we began to monitor temperature histories of the five structures. Temperatures were monitored in five locations: shingles, sheathing (two measurements), rafter, attic air, and outside ambient air. Shingle temperature was measured using a type-T thermocouple embedded at the midpoint of the shingle cross section and located about one-third the distance from the roof line, between the peak and lower eave. The other thermocouples (also type-T) were placed as follows: (a) embedded between the OSB or plywood sheathing and the roofing paper; (b) embedded about 0.5 mm into the bottom layer of the sheathing; (c) embedded at the midpoint of the nominal 2 by 6 (38 by 140 mm) rafter; and (d) suspended 200 mm away (extending inside) from the back wall, about 1.55 m from the floor. A single thermocouple, located under a metal shield (i.e., covered) about 50 mm away (extending outside) from the back wall and about 2 m above the ground, was used to measure outside air temperature. At each type-T thermocouple location, temperature data were collected every 5 minutes; an hourly average was recorded using a Campbell-Scientific (Logan, Utah) model CR10 data logger and a model AM416, 32-channel multiplexer. The data logger had a reported accuracy of 0.2 percent over a service temperature range of −55 to 85 °C.

Figure 2. — Side view of installed shingles: (a) western redcedar (WRC), (b) wood-thermoplastic composite (WTPC), and (c) fiberglass.

Individual temperature histories of WRC and WTPC shingles exposed in Wisconsin were monitored from January 2003 to December 2005 to assess the influence of the shingles on solar-induced thermal loads imparted to the wood roof truss lumber, OSB roof sheathing, and attic air temperatures experienced in traditional North American light-framed constructions. Each annual temperature history was compared with that of similarly designed roof assemblies under traditional black and white fiberglass shingles. To analyze and understand the temperature histories and relationships between various shingle systems and wood roof-system components, we accumulated the number of hours recorded for each thermocouple into 5 °C temperature bins. These 5 °C bins (0 to <5 °C, 5 to <10 °C, . . . , 70 to 75 °C) are hereafter defined as “exceedence temperatures.” For any roof configuration, the value reported as the exceedence temperature for 70 °C is thus the number of hours that the temperature at that thermocouple location equaled or exceeded 70 °C but was lower than 75 °C.

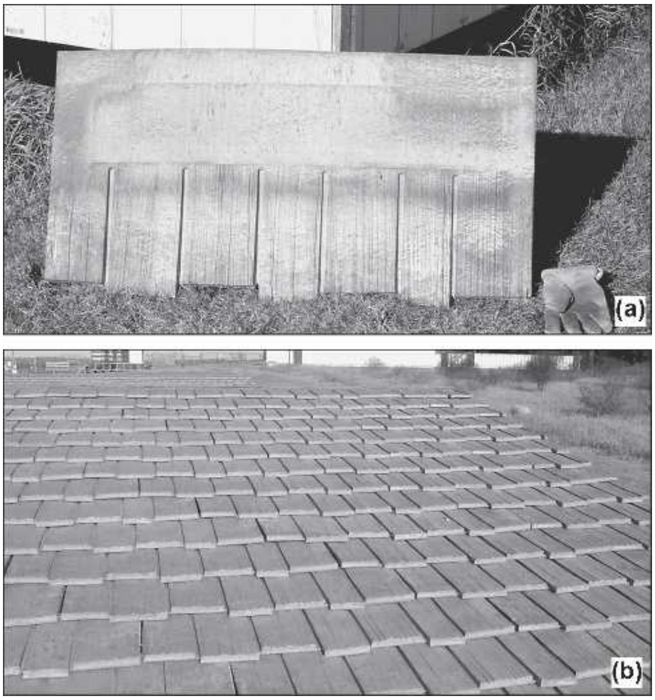

Figure 3. — Components for WTPC structure: (a) roof tiles, (b) shingles.

Results and discussion

Any analysis of thermal load data on roof-system performance depends on weather. A comparative review of several important weather-related parameters as recorded at the National Oceanic and Atmospheric Administration weather station at the Dane County Regional Airport in Madison, Wisconsin, is presented in **Table 1** (NOAA 2004, 2005, 2006). Our review of 2003, 2004, and 2005 weather data indicated that the weather in 2003 was virtually the same as the 64-year running average for temperature and precipitation. The 2003 June, July, and August temperatures averaged about 0.4 °C warmer than the 64-year average. In contrast, the summer weather in Madison in 2004 and 2005 was 1.4 °C cooler and 1.6 °C warmer than the NOAA running average for this area. The total annual precipitation in 2003 was near average, whereas 2004 and 2005 precipitation levels were 24 percent above and 22 percent below average, respectively (**Table 1**). Although summer 2005 generally experienced above-average temperatures, the winter months of early 2005 were much warmer than normal. In fact, the winter of 2004–2005 was one of the warmest in NOAA-recorded history. This warm winter heavily influenced 2005 average temperatures, which when casually compared seem higher than the 2003 and 2004 averages (**Table 1**). Previous work on the effects of thermal loads on wood properties has shown that a few hours at high temperatures (e.g., >50 °C) are significantly more influential than many times more exposure to cold weather (e.g., <25 °C) (Lebow and Winandy 1999). Thus, this warm winter of early 2005 must always be considered in any analysis of the implications of this thermal load data, and the reader is cautioned to consider such when drawing conclusions. The Forest Products Laboratory (FPL) field exposure facility is approximately 15 km west-southwest of the NOAA weather station.

Table 1. — Comparison of NOAA-reported annual weather data for Madison, Wisconsin (NOAA 2004, 2005, 2006).

	Year		
	2003	2004	2005
Average annual temperature (°C)	7.8	8.3	9.1
Difference from +60-year average annual temperature (°C)	–0.1	0.5	1.2
Total precipitation (mm)	805	1,001	627
Total snowfall (mm)	752	752	1,600
Average daily summertime maximum temperature (°C)			
May	19.0	19.7	19.1
June	25.1	24.2	28.5
July	26.9	26.1	28.6
August	28.9	23.8	27.5
September	22.3	25.1	26.0
Five-month average daily summertime maximum temperature (°C)	24.4	23.8	25.9
Total number of days >31 °C	9	0	13
May	0	0	0
June	2	0	4
July	0	0	5
August	7	0	2
September	0	0	2
Heating (°C days)	4,092	3,852	3,801
Cooling (°C days)	308	250	470

The scope and magnitude of the 2003 to 2005 temperature data preclude their full inclusion in this report. A detailed review of the data and an extensive series of graphical comparisons are available (Winandy et al. 2005, Winandy 2006). **Tables 2** to **4** summarize measured thermal load data for exposure structures in Madison, Wisconsin, for the years 2003 to 2005, respectively. Annual temperature histories (−35 to >70 °C) were calculated for shingles, top and bottom surfaces of roof sheathing, roof rafter, and attic air. **Figure 4** shows a sample temperature history for 2005 for various types of shingles and the sheathing beneath them.

Annual average, minimum, and maximum temperatures for each roof-system component are given in **Table 5**. On the warmest summer days, black fiberglass shingles were more than 10 °C warmer than matched white fiberglass shingles and about 20 to 25 °C warmer than comparable WRC or WTPC shingles. The composite sheathing and lumber rafters in the various roof assemblies and the attic air followed the same general temperature trends (**Table 5**).

Average hourly summer temperatures of plywood sheathing under black and white fiberglass shingles were generally 2 to 5 °C warmer than the shingle temperatures themselves. This is probably a function of the potential loss in radiant and/or convective energy possible for the cladding materials but limited for the sheathing. Summer temperatures of sheathing under WTPC and WRC shingles were virtually the same and generally 12 to 15 °C cooler than temperatures under fiberglass shingles. This could be a material issue, or more than likely it is related to the irregular bottom surface of the natural WRC shingles or the waffle-like construction of the WTPC shingles. The sheathing under WTPC shingles applied on lath was 4 to 5 °C cooler than sheathing under WTPC shingles installed directly on felt over the sheathing. This finding supports the opinion that the irregular bottom surface of the

Table 2. — Cumulative time within each exceedence temperature range in Madison, Wisconsin, from January 1 to December 31, 2003.

		Time (h) at various exceedence temperatures																					
		Degrees below 0 °C							Degrees above 0 °C														
Shingle[a]	Temp site[b]	>35	>30	>25	>20	>15	>10	>5	>0	>5	>10	>15	>20	>25	>30	>35	>40	>45	>50	>55	>60	>65	>70
Black	Shngl	2	17	102	248	414	547	987	1164	1011	1093	891	522	347	271	273	259	205	188	135	65	18	1
	Top	1	18	103	260	415	541	960	1137	988	1095	848	525	322	289	247	236	221	208	178	108	52	8
	Bot	--	2	44	213	410	563	947	1165	1036	1044	995	729	440	397	358	255	147	15	--	--	--	--
	Rafter	--	1	34	205	396	584	930	1193	1019	1052	1019	781	501	433	329	241	42	--	--	--	--	--
	Attic	--	1	33	204	401	589	946	1172	1031	1035	1023	780	503	435	328	241	38	--	--	--	--	--
WRC	Shngl	--	4	53	210	410	569	957	1221	1049	1085	996	772	488	426	304	197	19	--	--	--	--	--
	Top	--	7	58	214	410	574	958	1219	1038	1097	989	734	475	419	311	211	46	--	--	--	--	--
	Bot	--	1	33	205	384	590	947	1214	1074	1070	1039	840	546	413	318	86	--	--	--	--	--	--
	Rafter	--	--	32	200	398	603	955	1229	1042	1074	1078	856	574	434	262	23	--	--	--	--	--	--
	Attic	--	--	29	199	380	590	954	1211	1078	1056	1065	880	563	444	278	33	--	--	--	--	--	--
WTPC with lath	Shngl	--	12	47	203	422	592	976	1225	1032	1098	1012	757	537	420	295	129	3	--	--	--	--	--
	Top	--	3	35	191	405	593	978	1222	1050	1079	1034	830	555	427	292	66	--	--	--	--	--	--
	Bot	--	1	34	203	401	615	950	1245	1029	1081	1058	861	576	432	249	25	--	--	--	--	--	--
	Rafter	--	--	31	189	398	600	951	1233	1073	1055	1080	925	604	404	214	3	--	--	--	--	--	--
	Attic	--	--	29	191	387	582	965	1230	1060	1059	1079	895	601	438	230	14	--	--	--	--	--	--
WTPC w/o lath	Shngl	--	4	41	201	405	572	987	1211	1055	1082	1023	792	517	431	294	142	3	--	--	--	--	--
	Top	--	7	54	211	421	589	974	1214	1051	1077	1010	727	503	406	310	182	24	--	--	--	--	--
	Bot	--	--	32	195	391	591	961	1232	1049	1065	1086	838	560	425	284	51	--	--	--	--	--	--
	Raft	--	--	31	191	392	599	958	1231	1061	1050	1097	892	582	434	228	14	--	--	--	--	--	--
	Attic	--	--	29	186	375	567	962	1224	1072	1050	1096	893	578	452	257	19	--	--	--	--	--	--
White	Shngl	3	26	135	270	405	590	1050	1151	1049	1083	873	499	364	322	296	268	214	125	36	1	--	--
	Top	1	21	125	264	401	578	1004	1178	1046	1090	886	505	359	321	277	279	231	143	48	3	--	--
	Bot	--	3	64	217	407	564	986	1216	1036	1113	977	668	497	424	352	205	31	--	--	--	--	--
	Rafter	--	5	74	213	426	579	1011	1213	1018	1099	1002	729	508	448	314	121	--	--	--	--	--	--
	Attic	--	2	53	210	400	562	974	1224	1058	1099	985	746	519	462	319	144	3	--	--	--	--	--

[a] Black = black fiberglass shingles; WRC = western redcedar; WTPC with lath = wood-thermoplastic composite shingles laid directly on felt; white = white fiberglass shingles.

[b] Shngl = shingles; top = top surface of roof sheathing; bot = bottom surface of roof sheathing; attic = attic air.

Table 3. — Cumulative time within each exceedence temperature range in Madison, Wisconsin, from January 1 to December 31, 2004.

		Time (h) at various exceedence temperatures																				
		Degrees below 0 °C							Degrees above 0 °C													
Shingle[a]	Temp site[b]	>35	>30	>25	>20	>15	>10	>5	>0	>5	>10	>15	>20	>25	>30	>35	>40	>45	>50	>55	>60	>65	>70
Black	Shngl	1	19	79	207	360	615	897	1021	1243	1160	994	535	387	282	264	229	192	154	94	42	9	--
	Top	1	24	80	205	362	602	895	991	1223	1140	958	539	372	310	245	245	201	174	129	65	19	4
	Bot	--	9	50	187	331	533	952	999	1204	1209	1167	723	477	385	326	175	56	1	--	--	--	--
	Rafter	--	6	54	173	321	530	988	1008	1194	1186	1188	812	516	417	277	110	4	--	--	--	--	--
	Attic	--	7	51	174	327	517	973	1020	1208	1206	1199	790	498	434	271	106	3	--	--	--	--	--
WRC	Shngl	--	9	56	188	334	560	974	1041	1249	1183	1191	762	504	424	238	69	2	--	--	--	--	--
	Top	--	14	59	190	329	576	985	1033	1230	1197	1173	749	475	421	258	90	5	--	--	--	--	--
	Bot	--	7	51	169	323	532	999	1045	1225	1223	1228	839	568	393	175	7	--	--	--	--	--	--
	Rafter	--	6	52	169	328	529	1000	1058	1218	1242	1242	902	583	376	77	2	--	--	--	--	--	--
	Attic	--	6	51	165	324	515	999	1034	1248	1239	1236	882	608	384	91	2	--	--	--	--	--	--
WTPC with lath	Shngl	--	9	52	192	357	551	982	1057	1242	1220	1170	784	554	404	185	25	--	--	--	--	--	--
	Top	--	7	47	176	337	557	969	1063	1234	1214	1192	855	593	391	144	5	--	--	--	--	--	--
	Bot	--	7	51	171	336	540	995	1043	1218	1262	1217	880	594	386	82	2	--	--	--	--	--	--
	Rafter	--	4	51	167	332	528	996	1058	1206	1241	1266	933	613	345	44	--	--	--	--	--	--	--
	Attic	--	6	50	161	325	533	978	1050	1220	1251	1236	915	619	378	62	--	--	--	--	--	--	--
WTPC w/o lath	Shngl	--	9	52	179	338	567	974	1050	1231	1196	1200	807	531	408	209	33	--	--	--	--	--	--
	Top	--	13	59	194	343	592	964	1043	1238	1194	1159	769	496	403	245	66	6	--	--	--	--	--
	Bot	--	6	50	168	324	549	988	1051	1215	1224	1233	870	577	396	128	5	--	--	--	--	--	--
	Rafter	--	6	49	169	325	539	1001	1059	1199	1225	1269	905	613	359	66	--	--	--	--	--	--	--
	Attic	--	5	49	160	314	536	972	1059	1202	1243	1229	925	599	406	83	2	--	--	--	--	--	--
White	Shngl	1	21	105	203	390	656	929	1032	1246	1188	961	549	410	324	274	247	158	73	15	2	--	--
	Top	1	18	97	205	372	643	942	1015	1225	1182	970	576	402	314	283	247	185	82	21	4	--	--
	Bot	--	14	57	184	334	586	950	1028	1254	1210	1134	729	473	440	294	92	5	--	--	--	--	--
	Rafter	--	13	66	182	337	596	961	1022	1260	1227	1164	767	509	443	213	24	--	--	--	--	--	--
	Attic	--	10	57	180	322	568	959	1035	1250	1222	1169	773	513	456	233	37	--	--	--	--	--	--

[a] Black = black fiberglass shingles; WRC = western redcedar; WTPC with lath = wood-thermoplastic composite shingles laid directly on felt; white = white fiberglass shingles.

[b] Shngl = shingles; top = top surface of roof sheathing; bot = bottom surface of roof sheathing; attic = attic air.

Table 4. — Cumulative time within each exceedence temperature range in Madison, Wisconsin, from January 1 to December 31, 2005.

		Time (h) at various exceedence temperatures																					
		Degrees below 0 °C							Degrees above 0 °C														
Shingle[a]	Temp site[b]	>35	>30	>25	>20	>15	>10	>5	>0	>5	>10	>15	>20	>25	>30	>35	>40	>45	>50	>55	>60	>65	>70
Black	Shngl	--	21	105	164	270	725	1202	919	831	911	986	679	392	340	313	270	245	177	125	67	18	--
	Top	--	20	107	165	266	730	1191	910	815	904	979	671	378	332	294	275	246	213	133	94	37	--
	Bot	--	--	73	143	235	680	1114	1007	845	885	1058	929	566	444	387	260	126	8	--	--	--	--
	Rafter	--	--	70	147	229	679	1099	1045	849	883	1062	976	610	472	370	226	43	--	--	--	--	--
	Attic	--	--	70	144	224	668	1093	1044	850	892	1070	970	610	476	378	230	41	--	--	--	--	--
WRC	Shngl	--	7	76	157	238	711	1177	1034	879	918	1092	955	578	467	320	141	10	--	--	--	--	--
	Top	--	7	76	161	247	717	1197	1011	859	926	1099	917	570	454	333	165	21	--	--	--	--	--
	Bot	--	--	70	144	237	691	1143	1085	857	936	1100	1026	634	482	289	65	1	--	--	--	--	--
	Rafter	--	--	68	147	226	701	1110	1126	862	934	1116	1060	661	503	226	20	--	--	--	--	--	--
	Attic	--	--	71	140	228	674	1098	1132	859	938	1124	1052	661	509	248	26	--	--	--	--	--	--
WTPC with lath	Shngl	--	7	67	162	235	741	1128	1078	859	960	1093	969	594	481	283	102	1	--	--	--	--	--
	Top	--	5	61	155	238	725	1101	1105	877	948	1099	997	655	486	267	41	--	--	--	--	--	--
	Bot	--	--	62	146	232	723	1103	1109	879	937	1123	1044	652	500	229	21	--	--	--	--	--	--
	Rafter	--	--	61	149	237	712	1071	1139	871	937	1131	1096	678	494	179	5	--	--	--	--	--	--
	Attic	--	--	67	135	233	699	1076	1134	857	943	1133	1068	687	512	207	9	--	--	--	--	--	--
WTPC w/o lath	Shngl	--	4	66	158	246	738	1116	1077	869	952	1092	979	592	464	291	112	4	--	--	--	--	--
	Top	--	7	66	170	263	748	1141	1044	863	949	1091	931	557	435	321	155	19	--	--	--	--	--
	Bot	--	--	63	150	237	726	1093	1119	860	948	1119	1019	641	488	261	36	--	--	--	--	--	--
	Raft	--	--	63	148	239	709	1086	1140	864	935	1123	1086	659	496	203	9	--	--	--	--	--	--
	Attic	--	--	66	140	230	696	1074	1141	848	946	1124	1069	660	527	226	13	--	--	--	--	--	--
White	Shngl	--	21	108	169	289	770	1287	891	847	931	1023	684	402	382	314	281	194	128	37	2	--	--
	Top	--	21	104	167	291	770	1256	887	839	928	1025	695	393	371	325	285	211	136	52	4	--	--
	Bot	--	--	82	153	258	709	1167	998	884	946	1075	881	554	449	371	204	29	--	--	--	--	--
	Rafter	--	--	81	155	247	707	1150	1026	889	965	1076	937	585	476	336	127	3	--	--	--	--	--
	Attic	--	--	77	149	250	677	1146	1042	892	940	1105	936	586	469	352	133	6	--	--	--	--	--

[a] Black = black fiberglass shingles; WRC = western redcedar; WTPC with lath = wood-thermoplastic composite shingles laid directly on felt; white = white fiberglass shingles.

[b] Shngl = shingles; top = top surface of roof sheathing; bot = bottom surface of roof sheathing; attic = attic air.

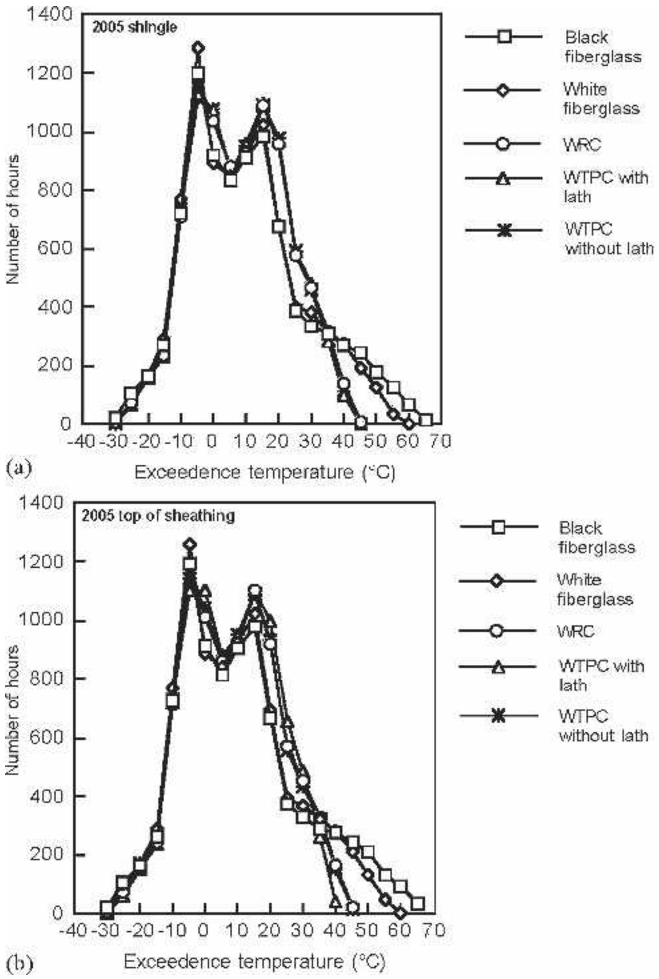

Figure 4. — Sample temperature history for 2005 for exposure of various types of (a) shingles and (b) top surface of composite roof sheathing.

natural WRC shingles or the waffle-like construction of the WTPC shingles creates airspace that enhances either radiant or convective cooling of sheathing.

These 3-year temperature history data and analysis indicates that during a typical winter season, temperatures of plywood roof sheathing under black and white fiberglass shingles are often 1 to 5 °C warmer than the shingles themselves. Temperatures of sheathing under WTPC and WRC shingles were generally the same (±1 °C) as shingle temperatures and virtually the same (±2 °C) as each other. Sheathing under WTPC shingles applied on lath was often 1 to 2 °C warmer in winter than sheathing under WTPC shingles installed on felt over the sheathing. Again, this general trend is similar to summertime observations and seems to support the hypothesis that radiant and possibly convective cooling are as critical as material differences.

No practical differences were noted in winter attic air temperatures in any system. In the summer, however, attic air temperatures were generally 3 to 7 °C warmer for structures with black fiberglass shingles than for the other shingle systems.

Overall roof temperature data recorded from July to September 2003 and 2005 for black and white fiberglass-shingled structures were correlated well and were very similar to those previously reported for this summer period in 2002 and in the 8-year period from 1992 to 1999 (Winandy et al. 2004, 2000, respectively). This allowed us to compare the 2003 to 2005 data with the previous 8-year annualized data from 1992 to 1999.

In comparing 2003 sheathing, rafter, and attic air temperature histories for black or white fiberglass shingles to the 8-year annualized (i.e., averaged) thermal load histories reported by Winandy et al. (2000), we found that in 2003, the summer tended to produce noticeably warmer top-of-sheathing temperatures and the winter tended to produce colder sheathing temperatures. The 2003 rafter and attic air temperature histories were similar to the 1992 to 1999 annualized data. The 2004 temperature histories of all roof-system components and of the attic air were similar to the 1992 to 1999 annualized data. We also found that whereas the 2005 summer weather tended to produce noticeably warmer top-of-sheathing temperatures, the warmer winter still tended to produce only average sheathing temperatures; this was probably related to the abundance of snowfall in 2005, which tends to insulate the roof system and hold it at or near the temperature of snow. This snow-effect condition was noted by Winandy and Beaumont (1995).

This agreement in data allowed us to compare the wealth of data on thermal load histories recorded for structures with black and white fiberglass shingles from 1992 to 1999 in both Wisconsin and Mississippi with these 3-year Wisconsin data for WRC and WTPC shingles. This agreement also makes it reasonable to apply cumulative thermal damage models to project long-term performance of wood sheathing and rafter materials under WTPC and WRC shingles because of the similarity of the 2003 to 2005 data to past performance data (1991 to 1999, 2002) for black and white fiberglass shingles.

The data on shingle, sheathing, and rafter performance have five important implications. First, the more than 50 years of field experience with fiberglass shingles over plywood and more than 25 years of field experience with OSB sheathing leave little doubt that some thermal degradation of untreated wood composite sheathing and wood truss lumber, however small and practically insignificant, may actually be occurring under black and white fiberglass shingles (Winandy 2001). Even a small level of degradation may eventually become of some practical importance for thinner sheathing used at maximum width span. The lower temperatures under WTPC and WRC shingles suggest that less thermal degradation of wood composite sheathing and wood rafters potentially occurs in such roof systems compared with systems that use black or white fiberglass shingles.

The second implication relates to whether it is air temperature, solar gain, or other variables controlling thermal loads experienced by various roof systems. Previous work (Winandy et al. 2000) on fiberglass shingles offered three hypotheses:

1. Daytime high temperatures at the top of the plywood roof sheathing were often controlled more by solar gain than by outside air or attic air temperatures.
2. Similarly, temperatures at the bottom of the roof sheathing were usually controlled by solar gain, except on a few of the hottest days, when sheathing temperatures were strongly influenced by outside air or attic air temperatures.
3. Finally, rafter temperatures were influenced by thermal radiation from sheathing but usually controlled by attic

Table 5. — Average, minimum, and maximum recorded temperatures experienced by the various components in the roof systems in Madison, Wisconsin, from January 1, 2003, to December 31, 2005.

Temperature site	Shingle type	2003 temperature			2004 temperature			2005 temperature		
		(°C)								
		Avg	Min	Max	Avg	Min	Max	Avg	Min	Max
Shingle	Black fiberglass	12.0	−30.6	70.7	11.8	−30.8	69.0	13.0	−28.7	68.3
	White fiberglass	10.5	−31.6	61.0	10.5	−30.7	60.7	11.5	−29.0	61.8
	WRC	10.3	−26.9	48.2	10.1	−27.3	46.9	10.9	−25.6	48.2
	WTPC with lath	9.9	−28.8	45.7	9.8	−27.7	44.1	10.6	−26.3	45.2
	WTPC w/o lath	10.1	−27.5	46.2	10.0	−27.1	44.6	10.7	−25.4	46.3
Sheathing top	Black fiberglass	12.8	−30.2	74.9	12.4	−30.6	72.2	13.4	−28.2	69.7
	White fiberglass	10.9	−30.2	61.4	10.8	−30.4	61.1	11.8	−28.3	62.5
	WRC	10.3	−27.2	49.1	10.1	−27.5	47.6	10.9	−25.8	49.6
	WTPC with lath	10.0	−26.6	43.5	9.9	−26.9	41.6	10.6	−25.6	43.2
	WTPC w/o lath	10.1	−27.5	48.2	9.9	−27.4	46.4	10.7	−25.8	48.7
Sheathing bottom	Black fiberglass	11.2	−25.8	52.4	10.9	−26.5	51.1	12.1	−24.8	52.2
	White fiberglass	10.3	−26.1	47.6	10.2	−27.0	47.2	11.1	−24.9	49.4
	WRC	10.2	−25.1	44.2	10.0	−26.1	42.7	10.8	−24.4	45.1
	WTPC with lath	9.8	−25.2	41.9	9.7	−26.4	40.6	10.6	−24.3	42.9
	WTPC w/o lath	10.0	−25.0	43.1	9.9	−26.0	41.8	10.7	−24.2	43.8
Rafter	Black fiberglass	10.8	−25.2	48.3	10.6	−26.2	46.7	11.8	−24.6	49.4
	White fiberglass	9.8	−26.4	44.7	9.8	−27.3	43.5	10.9	−24.7	46.3
	WRC	9.9	−24.8	42.1	9.7	−26.1	40.3	10.6	−24.2	42.9
	WTPC with lath	9.8	−24.4	40.6	9.7	−26.0	39.3	10.5	−24.1	41.3
	WTPC w/o lath	9.9	−24.5	41.3	9.7	−26.1	39.9	10.5	−24.0	41.9
Attic air	Black fiberglass	10.8	−25.1	48.5	10.6	−26.3	46.9	11.9	−24.2	49.5
	White fiberglass	10.2	−25.5	45.4	10.1	−26.6	44.1	11.0	−24.4	46.8
	WRC	10.1	−24.5	42.7	9.9	−25.9	40.6	10.8	−23.9	42.9
	WTPC with lath	10.0	−24.4	41.3	9.9	−26.1	39.4	10.7	−23.9	41.9
	WTPC w/o lath	10.2	−24.3	42.1	10.0	−25.7	40.3	10.8	−23.7	42.3

air temperatures, except on a few of the hottest days, when they were more strongly influenced by solar radiation.

The analysis of WTPC and WRC shingles showed virtually the same trends as these previously reported for fiberglass shingles. This analysis employing different roof cladding materials seems to fully support and those previous hypotheses.

The third implication comes from the comparison of thermal loads under WTPC shingles installed directly on felt over sheathing with thermal loads under WTPC shingles installed over lath. The 3-year sheathing data suggest that lower sheathing temperatures can be obtained by using lath between the shingles and sheathing, but the use of lath apparently does not reduce rafter or attic air temperatures (**Tables 1** to **3**).

The fourth implication pertains to the potential increase in service life resulting from lower shingle, sheathing, and rafter temperatures. We found that attic air temperatures were practically the same under all roof-covering materials during the winter, but the same attic air temperatures were measurably warmer during the summer in structures with black or white fiberglass shingles compared with WRC or WTPC shingles. This finding appears to agree with the findings of Holton and Beggs (1997). This reduced attic air temperature could undoubtedly have implications on overall energy costs when using summer air-conditioning. To estimate the relative magnitude of the energy-saving potential, we calculated the difference in attic air temperatures under each roof-covering material whenever the outside air temperature exceeded 25 °C. The critical outside air temperature of 25 °C or above was arbitrarily selected but thought to represent a limit at which most homeowners would choose to use an air conditioner. This summertime comparison of our 3-year attic air temperature histories proves that the type of shingle can make a difference of as little as 0.5 °C to as great as 4.4 °C in attic air temperature (**Table 6**). The implications of such differences in attic air temperature might result in measurable and possibly significant energy-saving potential in regions warmer

Table 6. — Differences between attic air temperature and various roof-cladding systems measured at outside air temperature ≥25 °C over 3-year period from 2003 to 2005.

Shingle type A	Shingle type B	Temperature difference		
		Mean	SD	Max
		(°C)		
Black fiberglass	White fiberglass	1.82	0.92	5.61
	WRC	4.00	2.13	9.00
	WTPC with lath	4.72	2.59	10.83
	WTPC w/o lath	4.37	2.37	9.83
WRC	White fiberglass	2.36	1.42	8.22
	WTPC with lath	0.83	0.55	2.56
	WTPC w/o lath	0.57	0.40	2.50
WTPC with lath	White fiberglass	3.08	1.78	8.17
	WTPC w/o lath	0.39	0.29	1.50
WTPC w/o lath	White fiberglass	2.73	1.55	7.00

than Wisconsin that heavily rely on summer air-conditioning. The lower temperatures measured under WTPC shingles could be related to the WTPC materials themselves or to the waffled construction of the lower surface of the WTPC shingle.

Finally, the 3-year field data clearly show that internal temperatures within WTPC shingles are well below the laboratory-derived thermal degradation temperatures of the high-density polyethylene mastic used in WTPC shingles of the type tested and currently being commercially used. Although we anticipate long-term stability of WTPC shingles in relation to thermal degradation, this study has not monitored the long-term UV-stability of these WTPC shingles. That work is currently underway.

Conclusions

Roof temperature histories are reported and analyzed for measured thermal loads of sheathing and rafters under western redcedar (WRC), wood-thermoplastic composite (WTPC), and black and white fiberglass shingles. The analyses clearly show that black fiberglass shingles experience much higher temperatures than do white fiberglass shingles. The WRC and WTPC shingles had similar internal temperatures and were cooler than either black or white fiberglass shingles. The analyses also indicate that during a typical summer or winter, sheathing under black and white fiberglass shingles is often warmer than the shingles themselves. Sheathing under WTPC and WRC shingles is much cooler than sheathing under fiberglass shingles. Sheathing under WTPC shingles applied over lath is noticeably cooler than sheathing under WTPC shingles installed on felt over the sheathing. The implications of these results are that lower in-service shingle, sheathing, and rafter temperatures should increase the expected service life of many roof-system materials. The type of shingle type may also have implications for overall energy costs because summer attic air temperatures were as much as 4.4 °C and 4.0 °C warmer under black fiberglass shingles than under WTPC or WRC shingles, respectively.

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