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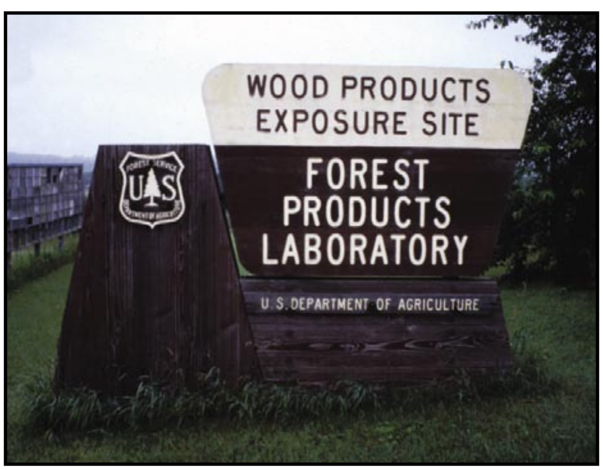
Two-Year Wisconsin Thermal Loads for Roof Assemblies and Wood, Wood–Plastic Composite, and Fiberglass Shingles

Jerrold E. Winandy
Michael Grambsch
Cherilyn A. Hatfield



Abstract

Temperature histories for various types of roof shingles, wood roof sheathing, roof rafters, and non-ventilated attics are being monitored in outdoor attic structures using simulated North American light-framed construction. This report presents 2-year data histories for annual thermal loads for western redcedar, wood–thermoplastic composite, and fiberglass shingles and for wood-based composite roof sheathing, wood rafters, and attics under these shingles.

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Two-Year Wisconsin Thermal Loads for Roof Assemblies and Wood, Wood–Plastic Composite, and Fiberglass Shingles

Jerrold. E. Winandy, Supervisory Research Wood Scientist
Michael Grambsch, Supervisory Electronics Technician
Cherilyn Hatfield, Statistician
Forest Products Laboratory, Madison, Wisconsin

Introduction

Comprehensive temperature histories for a roof system under fiberglass shingles were recorded and reported after 8 years in Madison, Wisconsin (43°N latitude), and 4 years in Starkville, Mississippi (33°N latitude) (Winandy and Beaumont 1995, Winandy and others 2000). Summer shingle temperatures for five types of shingle materials and their resulting influence on the roof system and attic temperatures were reported by Winandy and others (2004). This data paper and a related report (Winandy 2005) are the next in a series of papers dedicated to quantifying field thermal loads on shingles, sheathing, rafter lumber, and attic air space in traditional North American light-framed construction. The overall program has involved a series of interrelated studies conducted over a 14-year period. Roof temperature data such as presented in this paper can also be applied to predictive roof-temperature models (TenWolde 1997) to make performance interpretations for other building designs. The project reported here 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 ultraviolet (UV) weathering for wood–thermoplastic roofing shingles.

Objective

An objective of the roof temperature assessment project is to collect field data documenting the actual thermal load history of various wood components and shingle materials as used in traditional light-framed structures. This report provides 2-year roof temperature histories as measured for a location in southern Wisconsin near Madison. Thermal load histories are critical parameters in assessing the long-term service life of roof coverings and materials within the entire roof system. Thermal load data are critical to any subsequent modeling of the rates of thermal degradation for roof shingles, wood composite sheathing, and rafter lumber (Lebow and Winandy 1999). They can also provide valuable insight into the influence of individual roof-system components on potential energy costs required to heat or cool the structure.

Figure 1—Exposure structures located at Forest Products Laboratory test site near Madison, Wisconsin. All five units were similar 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 and further without lath), and white fiberglass shingles.

Methods

Exposure Structures

In the summer of 1991, five field exposure structures (Fig. 1) were constructed near Madison, Wisconsin (43° latitude). In Madison, the average incidence angle of sunlight is 19.5° from the southern horizon on the winter solstice (December 21) and 43° on the summer solstice (June 21). The annual average declination angle is 31.25°. The Wisconsin exposure structures (WI structures) were constructed to face south in a shadeless area open to direct sunlight. The structures were spaced far enough apart to prevent any one structure from shading the next structure. Winandy and Beaumont (1995) described the construction of the WI structures in detail and reported 3-year annualized data.

In 1994, matched exposure structures were built at the Mississippi Forest Products Laboratory, Mississippi State

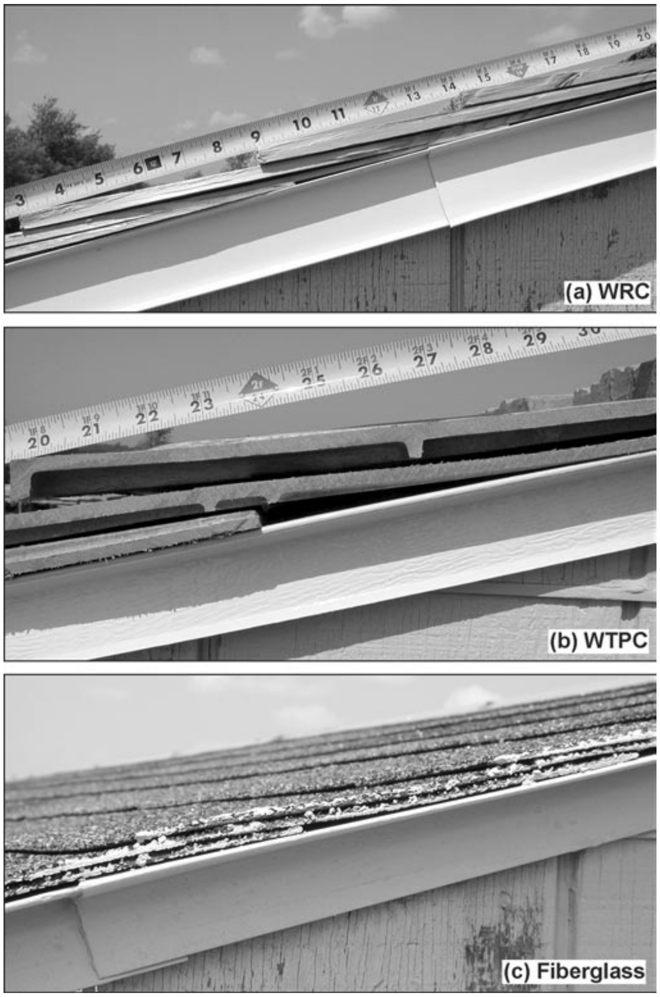

Figure 2—Side view of installed shingles: (a) western redcedar (WRC), (b) wood–thermoplastic composite (WTPC), and (c) fiberglass.

University, in Starkville, Mississippi (33.5° latitude), as part of an ongoing effort to relate temperatures histories in matched northern to southern U.S. roof systems. In Starkville, the average incidence angle of sunlight is 32.3° from the southern horizon on the winter solstice and 74.8° on the summer solstice. The annual average declination angle is 53.5°. The exposure structures in Mississippi (MS structures) were constructed to face south in a shadeless area open to direct sunlight. As for the WI structures, the MS structures were spaced far enough apart to prevent any one structure from shading the next structure. The data from the MS structures provide a direct measure of a more severe (higher solar loading) location compared with Madison, Wisconsin.

The WI and MS structures were identical. The structures were 3.7 m wide by 4.9 m long and constructed to simulate part of a typical multifamily attic–roof system in which U.S. Model Building Codes sometimes allow the use of fire-retardant-treated plywood roof sheathing. To replicate this type of construction on a smaller scale, the 3.7-m-wide structures simulated in cross section the 1/8- to 3/8-span section of a 14.8-m span, 3:12 pitch roof system in both roof area and attic volume (Winandy and Beaumont 1995). Each exposure structure was completely enclosed and unventilated. The four exterior walls were sheathed with 12-mm-thick, 200-mm-grooved Southern Pine siding attached to nominal 2- by 4-in. (standard 38- by 89-mm) wall studs. The exterior surfaces were painted with a light gray (almost white) paint. The walls, floors, and roof system were not insulated.

Recording of Temperature

To assess the effect of fiberglass shingle color, from 1991 to 2001 the WI structures were roofed with black or white fiberglass shingles weighing 106 kg/square. The MS structures were roofed with black fiberglass shingles. The fiberglass shingle manufacturer reported reflectance values of 3.4% and 26.1% for matched black and white shingles, respectively. Both black and white shingles had an emissivity rating of 0.91 as reported by the manufacturer. The WI and MS structures were instrumented with type-t thermocouples placed at various locations within the structures.

In the fall of 2001, the shingles and plywood sheathing were removed from one white-shingled and two black-shingled 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 (Figs. 1 and 2). The WTPC shingles were 0.86 m wide by 0.45 m high, made from a 50/50 blend of wood flour and high-density polyethylene, and compression molded (Fig. 3). In one WTPC construction, the 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, the shingles were laid over a horizontal course of 9-mm-thick lath that, in turn, was laid over a similar vertical course of lath.

We began monitoring the temperature histories of the five WI structures in the summer of 2002. As described in the previous text, in four of these structures the shingles (WRC, WTPC, white fiberglass, and black fiberglass) were applied directly over felt (i.e., without lath). In the fifth structure, WTPC shingles were applied over lath. Temperatures were monitored in five locations: shingles, sheathing (two measurements), rafter, attic air, and outside ambient air. The shingle temperature was measured using a type-t thermocouple embedded at the mid-point of the shingle cross-section and located about one-third the distance from the roof line, between the peak and lower eave. Type-t thermocouples were also placed as follows: (a) embedded between OSB or plywood sheathing and roofing paper; (b) embedded about 0.5 mm into bottom layer of sheathing;

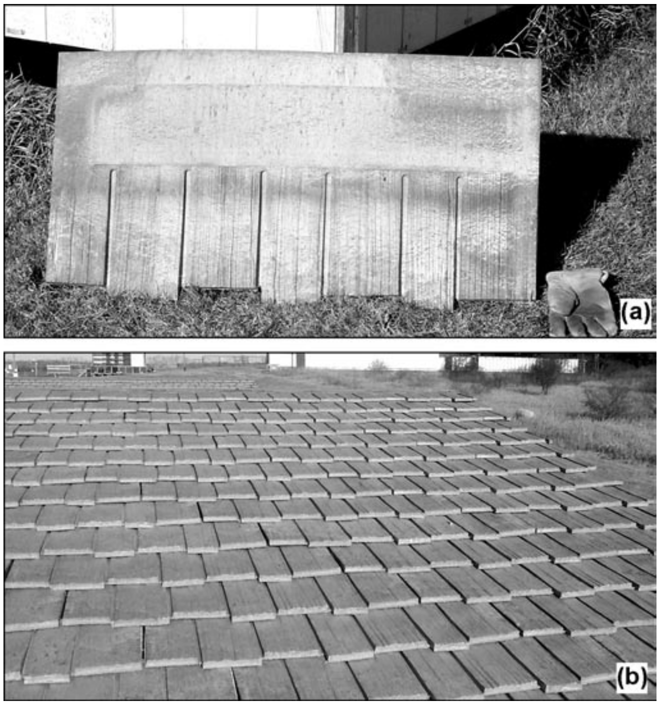

Figure 3—Components for WTPC structure: (a) roof tiles, (b) shingles.

(c) embedded at mid-point of nominal 2 by 6 (38- by 140-mm) rafter; and (d) suspended 200 mm away (extending inside) from back wall, about 1.55 m from floor. To measure the outside air temperature, a thermocouple was located under a metal shield (i.e., covered) about 50 mm away (extending outside) from the back wall, about 2 m above the ground. A detail description of thermocouples and installation was reported previously (Winandy and Beaumont 1995).

At each thermocouple location, temperature data were collected every 5 min; 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% over a service temperature range of 55°C to 85°C. The Wisconsin installation as reported for 2003 and 2004 was identical to that used by Winandy and others (2004).

The individual temperature histories of WRC and WTPC shingles exposed in Wisconsin were monitored from January 2003 to December 2004 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 then compared to that of similarly designed roof assemblies under traditional black and white fiberglass shingles.

To develop the temperature history for each roof covering and component, we calculated the number of hours recorded for each thermocouple into 5°C temperature bins. These 5°C bins (0°C to <5°C, 5°C to <10°C, …, 70°C to 75°C) are hereafter defined as "exceedence temperatures." 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.

Results and Discussion

Tables 1 and 2 show data for exposure structures in Madison, Wisconsin, for the years 2003 and 2004, respectively. Annual temperature histories (–40°C to 75°C) for 2003 and 2004 were calculated for shingles (Fig. 4), top and bottom surfaces of roof sheathing (Figs. 5 and 6), rafters (Fig. 7), and attic air (Fig. 8).

The 2-year mean annual temperatures recorded for shingles during this period were 11.9°C and 10.5°C for black and white fiberglass shingles, respectively; 10.2°C for WRC shingles; and 9.9°C and 10.1°C for WTPC shingles with and without lath, respectively. The maximum temperatures recorded during this period were 70.7°C and 61.0°C for black and white fiberglass shingles, respectively; 48.2°C for WRC shingles; and 45.7°C and 46.2°C for WTPC shingles with and without lath, respectively. On the warmest summer days, black fiberglass shingles were more than 10°C warmer than matched white fiberglass shingles and almost 22°C to 25°C warmer than comparable WRC or WTPC shingles.

The temperatures of the other components in the various roof assemblies and the attic air temperatures followed the same trends. The maximum temperatures recorded at the top layer of the roof sheathing were 74.9°C and 61.4°C for black and white fiberglass shingled roofs, respectively; 47.6°C for WRC; and 43.5°C and 48.2°C for WTPC with and without lath, respectively. For the bottom layer of the roof sheathing, the maximum temperatures recorded were 52.7°C and 46.6°C for black and white fiberglass shingles, 44.1°C for WRC, and 43.3°C and 44.2°C for WTPC with and without lath, respectively. For the rafter, the maximum temperatures were 49.1°C and 43.8°C for black and white fiberglass shingles, 42.1°C for WRC, and 42.0°C and 42.4°C for WTPC with and without lath, respectively. The maximum attic air temperatures were 48.9°C and 44.1°C for black and white fiberglass shingles, 42.6°C for WRC, and 42.4°C and 42.6°C for WTPC with and without lath, respectively.

The overall roof temperature data recorded from July to September 2003 and 2004 (Tables 1 and 2) for both black and white fiberglass shingled structures were found to be very similar to data previously reported for July to September 2002 (Winandy and others 2004) and over an 8-year period from 1992 to 1999 (Winandy and others 2000). We also compared the sheathing, rafter, and attic air temperature histories for 2003 to the previously reported 8-year annualized (i.e., averaged) thermal load histories

(Winandy and others 2000). We found that temperatures were more extreme in 2003: noticeably warmer exposure temperatures occurred in the top of the sheathing in the summer of that year and colder temperatures in both the top and bottom of the sheathing in the winter (Fig. 9). The 2003 rafter and attic air temperature histories were similar to the 1992–1999 annualized data (Fig. 10). The 2004 temperature histories of all roof-system components and the attic air temperatures were found to be similar to the 1992–1999 annualized data (Figs. 11, 12).

Conclusion

This paper describes 2-year thermal load histories of various wood components in traditional light-framed structures using western redcedar, wood–thermoplastic composite (WTPC), or black and white fiberglass shingles. The data clearly show that in the summer the temperature of black fiberglass shingles is much higher than that of white fiberglass shingles. Western redcedar (WRC) and WTPC shingles have similar temperatures but are cooler than either black or white fiberglass shingles. The data also indicate that during a typical summer or winter season, the sheathing under both black and white fiberglass shingles is sometimes warmer than the shingles themselves. The temperature of sheathing under WTPC and WRC shingles is virtually the same, but generally much cooler than that of sheathing under fiberglass shingles. Sheathing under WTPC shingles applied on lath is noticeably cooler than sheathing under WTPC shingles installed directly on felt.

A detailed analysis of these thermal load histories is available (Winandy 2005). That report also includes a comprehensive comparison of the thermal load histories to previous findings.

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

		Time (h) at various exceedence temperatures (°C)																					
		Below 0°C							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 is black fiberglass shingles; WRC, western redcedar; WTPC with lath, wood–thermoplastic composite shingles laid on lath; WTPC w/o lath, wood–thermoplastic composite shingles laid directly on felt; white, white fiberglass shingles.
[b] Shngl is shingle; top, top surface of roof sheathing; bot, bottom surface of roof sheathing; attic, attic air.

Table 2—Cumulative time within each exceedence temperature range in Madison, Wisconsin, from January 1 to December 31, 2004

		Time (h) at various exceedence temperatures (°C)																					
		Below 0°C							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	—	21	105	203	390	656	929	1032	1246	1188	961	549	410	324	274	247	158	73	15	2	—	—
	Top	—	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 is black fiberglass shingles; WRC, western redcedar; WTPC with lath, wood–thermoplastic composite shingles laid on lath; WTPC w/o lath, wood–thermoplastic composite shingles laid directly on felt; white, white fiberglass shingles.
[b] Shngl is shingle; top, top surface of roof sheathing; bot, bottom surface of roof sheathing; attic, attic air.

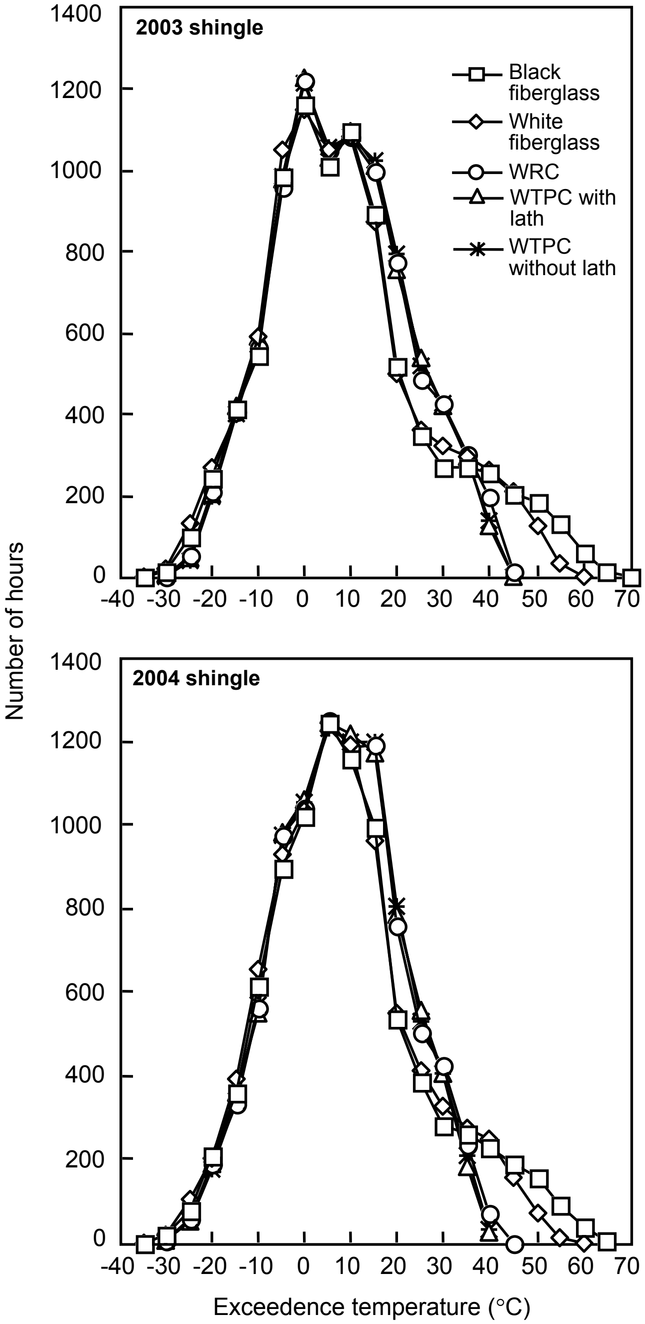

Figure 4—Cumulative temperature histories of WTPC (with and without lath), WRC, and fiberglass shingles exposed from January to December in 2003 and 2004 near Madison, Wisconsin.

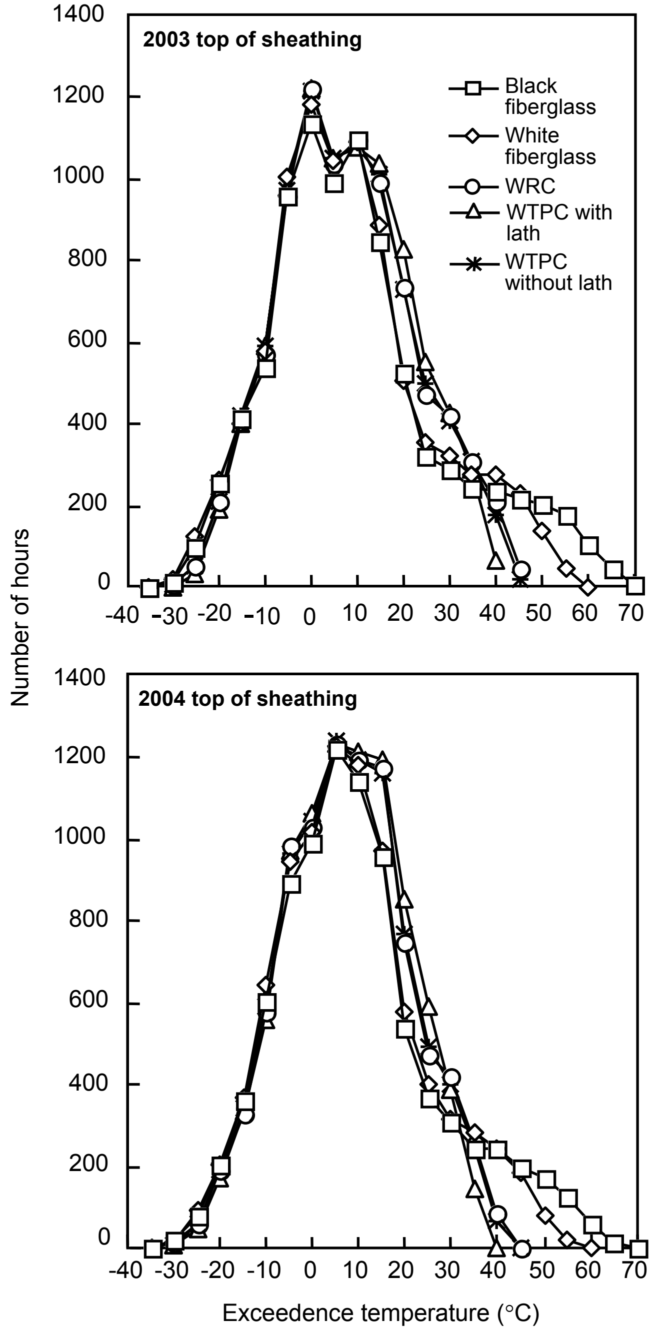

Figure 5—Cumulative temperature histories at top surface of roof sheathing under various types of shingles.

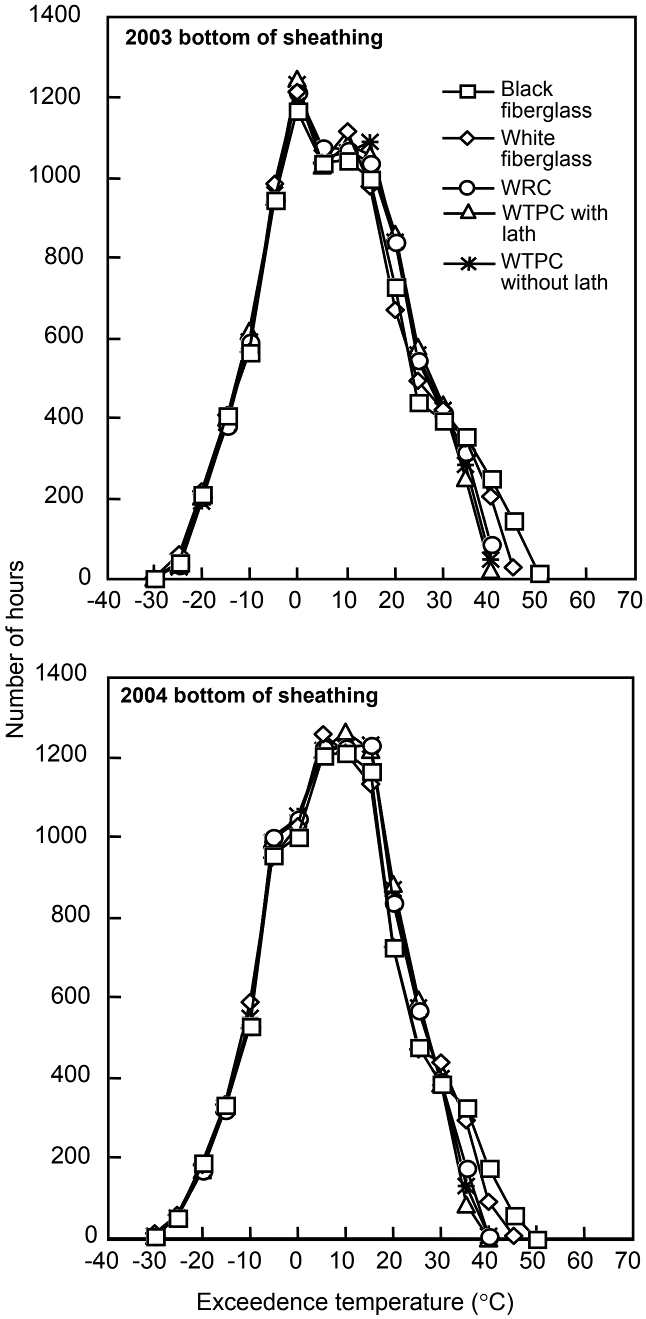

Figure 6—Cumulative temperature histories at bottom surface of roof sheathing under various types of shingles.

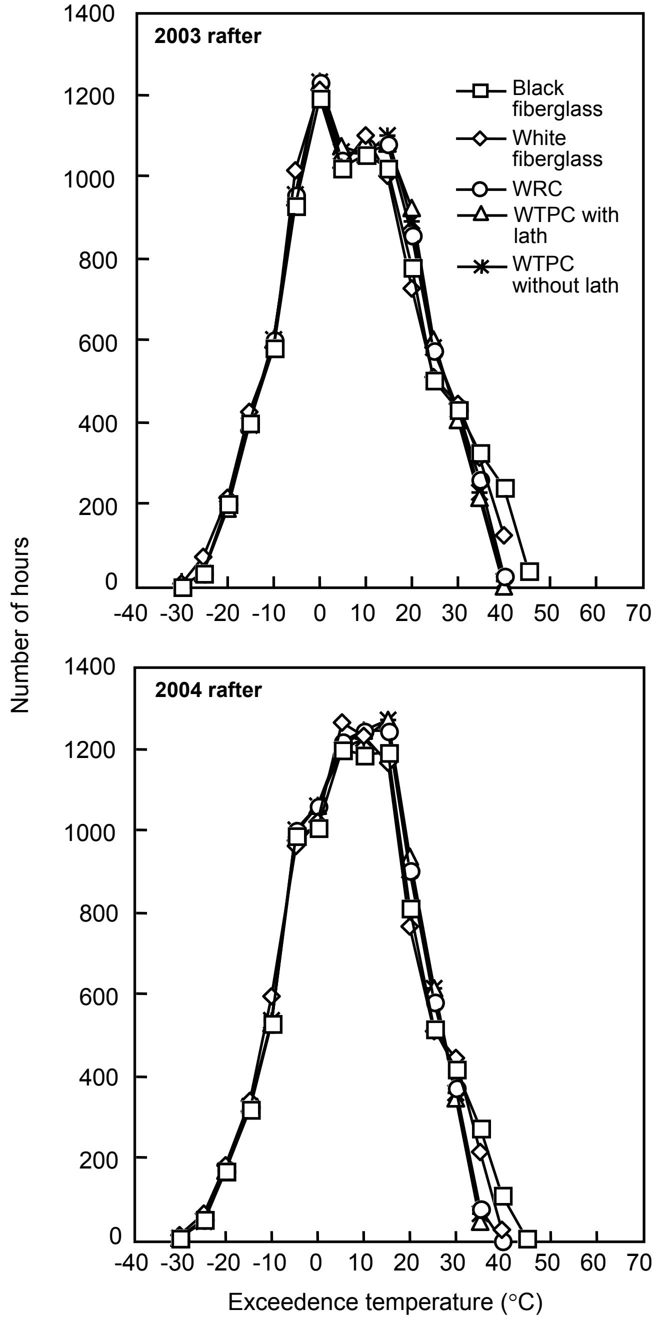

Figure 7—Cumulative temperature histories of interior core of roof rafters supporting sheathing under various types of shingles.

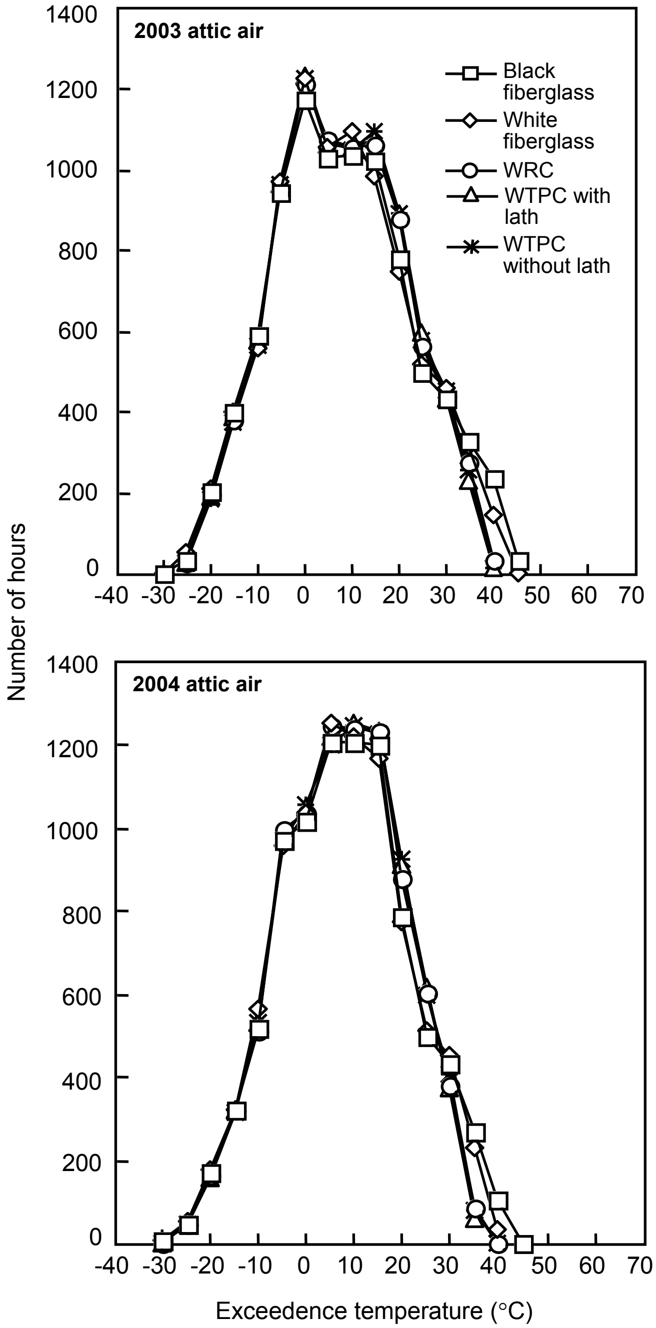

Figure 8—Cumulative temperature histories of attic air temperature in structures made with various types of shingles.

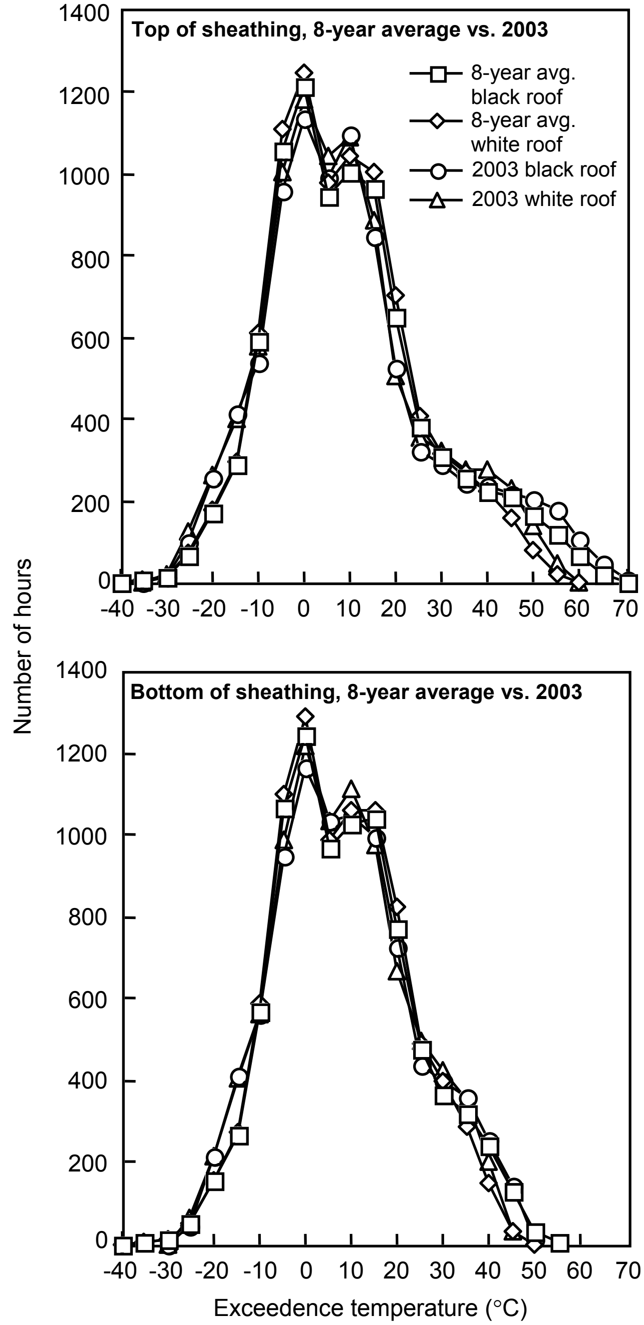

Figure 9—Cumulative temperature histories at top and bottom of sheathing in structures with black and white fiberglass shingles exposed from January to December 2003 compared to 8-year (1992–1999) annualized data (Winandy and others 2000).

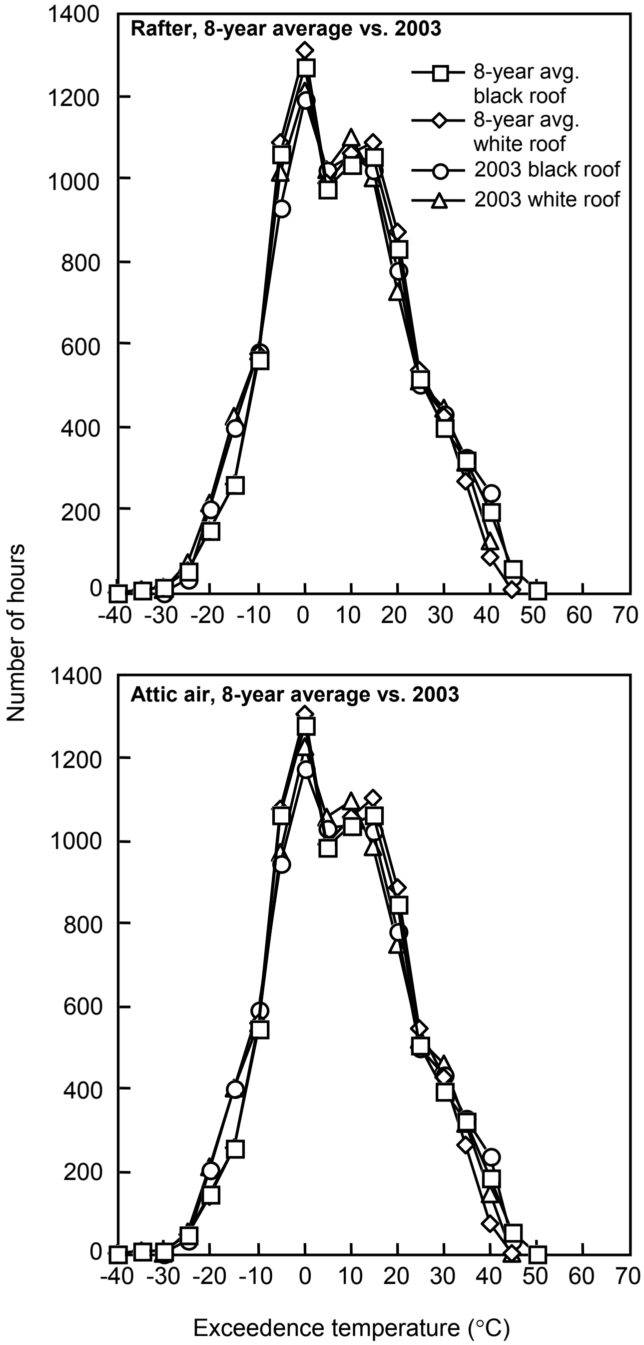

Figure 10—Cumulative temperature histories of rafters and attic air in structures with black and white fiberglass shingles exposed from January to December 2003 compared to 8-year annualized data.

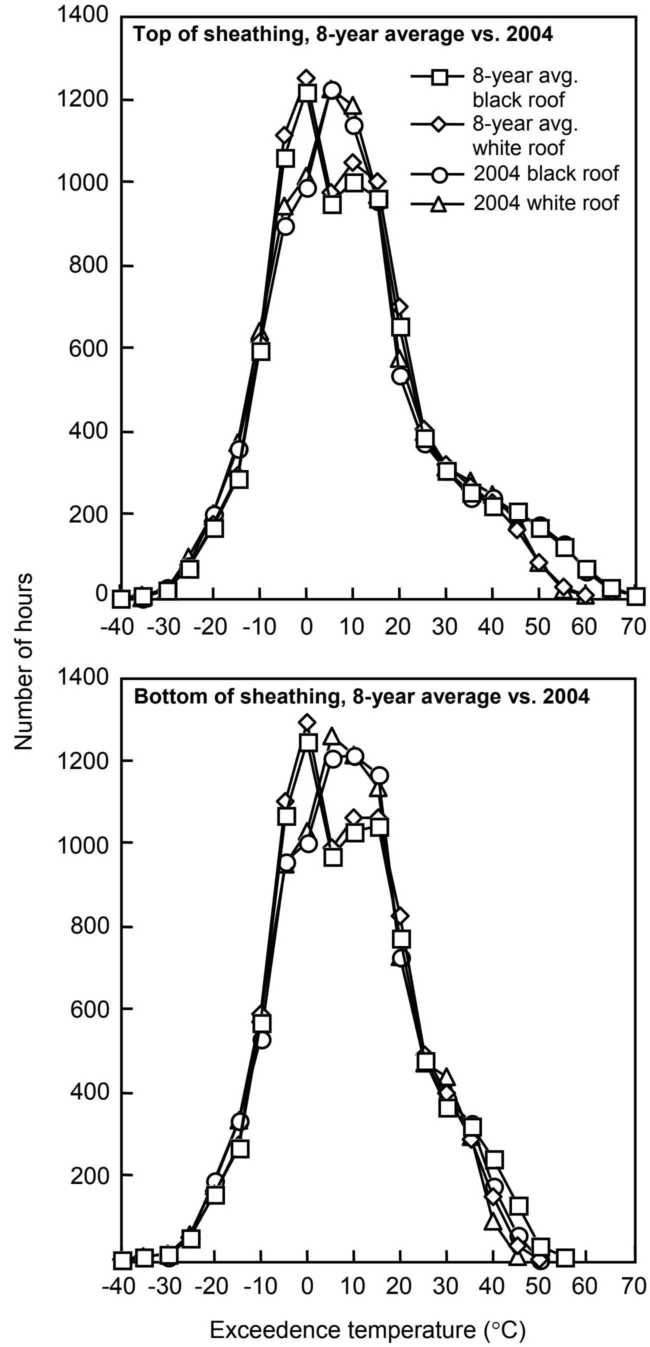

Figure 11—Cumulative temperature histories at top and bottom of sheathing in structures with black and white fiberglass shingles exposed from January to December 2004 compared to 8-year annualized data.

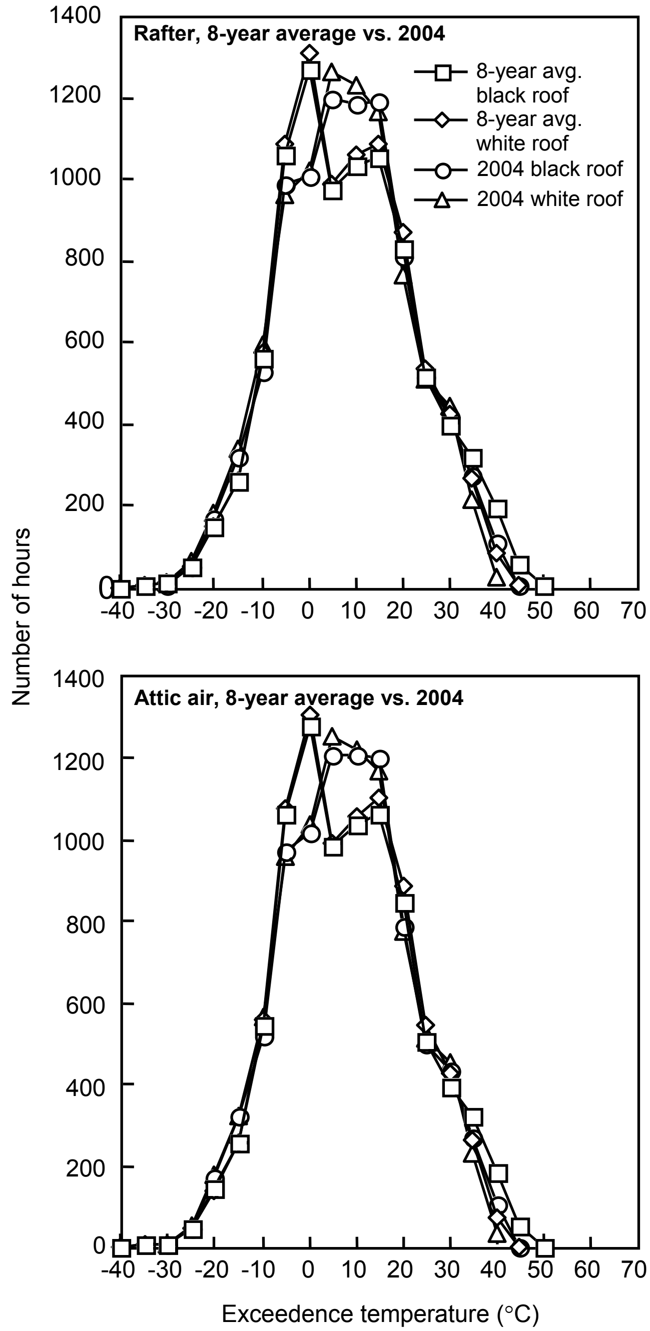

Figure 12—Cumulative temperature histories in rafters and attic air in structures with black and white fiberglass shingles exposed from January to December 2004 compared to 8-year annualized data.