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Roof Temperatures in Simulated Attics

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Abstract

The degradation of wood treated with fire retardant (FR) chemicals in roof systems is a problem of major national significance. Understanding of this phenomenon is limited by lack of information on how the performance of FR-treated wood in the laboratory correlates to that of FR-treated wood in the field. In this study, five outdoor field exposure chambers were constructed near Madison, Wisconsin, in the summer of 1991. These structures were intended to simulate the "attics" of multifamily structures for which model building codes sometimes allow the use of FR-treated roof sheathing. Interior attic air, exterior air, inner and outer sheathing, and internal rafter temperatures of black- and white-shingled chambers were monitored. Temperatures were measured using thermocouples and recorded over a 3-year period from October 1991 through September 1994 using a datalogger/multiplexer device. Overall, the plywood sheathing in black-shingled roof systems tended to be 10˚F to 15˚F (5˚C to 8˚C) warmer during the midafternoon of a sunny day than the plywood in comparable white-shingled roof systems. The maximum sheathing temperatures recorded were 168˚F (76˚C) for black-shingled roofs and 147˚F (64˚C) for white-shingled roofs. The results suggest that roof-sheathing plywood and roof-truss lumber temperatures, which are the primary factors that influence thermal degrade of FR-treated materials, are primarily controlled by solar gain rather than attic ventilation or attic insulation. These results are tempered by the fact that the effect of moisture content was not evaluated nor was moisture controlled by attic ventilation.

Keywords: Roof temperature, plywood, roof sheathing, rafter, thermal degrade, fire-retardant treatment, shingles, attic ventilation

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Problem

The degradation of wood treated with fire retardant (FR) chemicals in roof systems has been reported in thousands of cases over the eastern half of the United States (NAHB 1990). Understanding of this wood deterioration phenomenon is currently limited since there is little information that correlates the results of laboratory experiments using steady-state and cyclic temperature exposures to actual diurnal (that is, daily cyclic) field temperature histories experienced by FR-treated wood in service. This lack of a consensus "lab-to-field" correlation has inhibited the ability to predict thermal-induced degradation of FR-treated wood in the field from thermal-degradation rates derived in the laboratory.

Current model studies have generally been limited to isothermal rate studies performed in the laboratory with selected model FR chemicals. Factors other than temperature appear to play a secondary role in the degradation of FR-treated wood. These secondary factors, which are currently being studied in greater detail in additional laboratory experiments, include relative humidity (as it influences wood moisture content) and moisture content cycling. Each factor (temperature and moisture content) contributes to the rate of thermal-induced degradation. However, a significant problem is the lack of reliable and scientifically reproducible data that relates the performance of FR-treated wood products in laboratory exposures to performance in the field. Accurate modeling of the degradation of FR-treated and untreated wood will require obtaining sufficient and comprehensive data from both laboratory and field studies to establish creditable acceptance criteria for evaluating roof sheathing performance.

Our study consists of three phases:

1. construction and monitoring of five field exposure chambers near Madison, Wisconsin,

2. exposure of side-matched specimens treated with various FR treatments in either a steady-state 150˚F (66˚C)/75-percent relative humidity laboratory exposure or a diurnal/seasonal exposure in one of these five field chambers, and finally

3. mechanical evaluation and development of a lab–field correlation factor.

This report presents actual roof temperature data from Phase 1 of this experiment obtained over a 3-year period from October 1, 1991, through September 30, 1994.

In Phase 2 of our experiment, the five field exposure chambers serve as platforms in which nominal 0.5-in.- (standard 12-mm-) thick, 4- by 22-in. (100- by 559-mm) plywood test specimens are being exposed to diurnal/seasonal cyclic field conditions. The inside of each exposure chamber was constructed such that 96 plywood samples could be inserted into the frames, providing direct contact with the shingle/roof felt roofing membrane. A future report will describe the potential for thermal degrade of untreated controls and various generic FR treatments exposed to either simulated field conditions in a field exposure chamber or to a steady-state high-temperature environment in the laboratory at 150˚F (66˚C) and 75 percent relative humidity.

Background

Fire retardants were first used in the United States by the Navy in 1895 (Moreel 1939), but use was discontinued in 1902, in part because of their corrosiveness to fasteners. Preliminary research by Prince (1915) and the Forest Products Laboratory, USDA Forest Service, in the 1930s (Hunt and others, 1930,1931,1932; Truax and others, 1933,1935) led to the use of combinations of ammonium sulfate, diammonium phosphate, borax, and boric acid as commercial fire retardants. Materials treated with these systems have been used successfully in structures at or near room temperature for more than 50 years. Histories of FR-treated wood and its acceptance by building codes and in treating standards, respectively, can be found in the literature (Catchpole 1976, Barnes 1994).

In the 1970s, concern over hygroscopicity and fastener corrosion led the industry to develop improved systems with lower corrosion potential and hygroscopicity, known generically as second-generation fire retardants (Davies 1979). These systems entered the marketplace in the early 1980s. At nearly the same time, a change in the model building codes allowed the use of FR-treated plywood sheathing as a replacement for noncombustible roof deck and parapet–wall systems in multi-family structures. Because of the energy crisis, construction practices were also changed to provide more resistance to passive indoor air infiltration, and designers relied more on built-in passive attic ventilation or active mechanical attic ventilation. In addition, structures were better insulated in an attempt to make them more thermally efficient. Each change had the potential for affecting the in-service temperatures to which wood roof systems were exposed.

Heyer (1963) reported temperature histories for wall and roof systems for six houses and one office building located across the United States. The houses were located in Tucson, Arizona; Athens, Georgia; Portland, Oregon; Diboll, Texas; and Madison, Wisconsin. The office building, the original headquarters of the Forest Products Society, was also located in Madison, Wisconsin. The results of this study found that the maximum temperature of the roofs could reach 170°F (76°C), but that the cumulative duration of temperatures over 160°F (71°C) was not observed to exceed 21 h in any one year. In addition, the cumulative duration of temperatures over 150°F (66°C) was not observed to exceed 64 h in any one year, which is important considering that design standards for wood (AF&PA 1991) require a strength property adjustment for sustained exposures above 100°F (38°C) and greater adjustment for prolonged exposure above 150°F (66°C).

Several studies modeled the roof temperatures attained by structural buildings. Ozkan and Wilkes studied the temperatures of the surface and various components in flat roof systems, but they did not consider wood sheathing temperatures. In the study by Ozkan (1993), temperatures on roofing surfaces of a field station in a very hot, dry Arabic climate reached 200°F (93°C) during April 1989 to November 1990. The primary use of this station was to observe the effects of weathering and to measure the temperatures of the bituminous and polymeric waterproofing membranes in addition to that of thermal insulation materials. In the study by Wilkes (1989), metal roof temperatures reached as high as 163°F (73°C) during January and May in eastern Tennessee. For more exposure temperature histories for shingles the reader is referred to publications by the National Bureau of Standards (NBS 1979) and Blackenstowe (1987). The temperatures histories discussed hereafter pertain to wood components of roof systems.

Computer models have been developed that predict the average temperature and moisture content of plywood roof sheathing and other lumber roof members based on various construction details, materials, ventilation factors, and solar gain (that is, radiation load) on the roof. A model studied by the American Plywood Association predicted that flat-roofed systems with a black membrane might experience high-end temperatures of 150±5°F (66±3°C), 160±5°F (71±3°C), 170±5°F (76±3°C), and 180±5 F° (82±3°C) for up to 36, 13, 5, and 2 h, respectively, over the course of an average year in Hartford, Connecticut (APA 1989). Wilkes (1989) developed and verified a predictive roof temperature model for multi-layer nonwood roof systems. However, the model does not account for moisture flux, which may be critical in wood roof systems.

TenWolde (1988) described a model (still under development and needing verification) that estimates that the surface temperature of plywood roof sheathing is dominated by solar gain and the heat exchange between the roof surface and ambient air. Diurnal temperature variation and hourly sheathing temperature histories are also influenced by the radiant energy absorptivity of roofing surface, the pitch of the roof, and the presence of insulation and attic ventilation. The TenWolde model predicts that wet plywood sheathing dries quickly under warm summer conditions. For example, if plywood with a moisture content of 60 percent is installed, the plywood moisture content is roughly 15 percent after 1 week and is reduced to 8 percent in roughly 2 weeks. The model also indicates that the absorptivity of solar/radiant energy of the roofing material has the greatest effect on increasing or reducing the average temperature of the plywood roof sheathing. If the absorptivity of the roofing material is 0.92, the model predicts that the maximum hourly temperature for the roof sheathing plywood is 140°F (60°C) and the maximum predicted exterior roof membrane temperature is 150°F (66°C). If the absorptivity is changed to 0.2, supposedly representing a metal roof system, the maximum predicted sheathing temperature drops to 95°F (35°C) and the maximum predicted membrane temperature is 95°F (35°C). The pitch of the roof has only a moderate influence on reducing both the exterior surface temperature and the average temperature of the plywood. The TenWolde model also predicts that the presence of insulation installed directly on the underside of the sheathing has virtually no influence on sheathing temperature on the top surface but raises the average sheathing temperature relative to that of the top surface. When the ventilation rate in uninsulated systems is increased from 8 air changes per hour to about 21, almost no reduction of the top surface sheathing temperature or average sheathing temperature is predicted.

In 1992, a test facility was constructed at the Building Research Council of the University of Illinois to measure heat transfer, moisture movement, and airflow in typical residential attic structures under natural conditions (Rose 1992). The results of this study showed that during the summer in Illinois attic ventilation could lower attic air temperature by 28°F (15.5°C) and sheathing temperature by almost 10°F (5.5°C). However, attic ventilation had only a minor effect on roof shingle temperature.

Method

To obtain the necessary roof sheathing temperature data to relate diurnal and seasonal-cyclic field exposure to steady-state laboratory exposures, five field exposure chambers were constructed at the Valley View exposure site near Madison, Wisconsin (43° latitude). On the winter solstice (December 21), the average incidence angle of sunlight is 19.5° from the southern horizon and on the summer solstice (June 21), 43°. Thus, the annual average declination angle in Madison is 31.25°. Considering these facts, the chambers were constructed to face south in a shadeless area open to direct sunlight. In addition, the chambers were also spaced far enough apart to prevent any one chamber from shading the next chamber. The exposure chambers are shown in Figure 1.

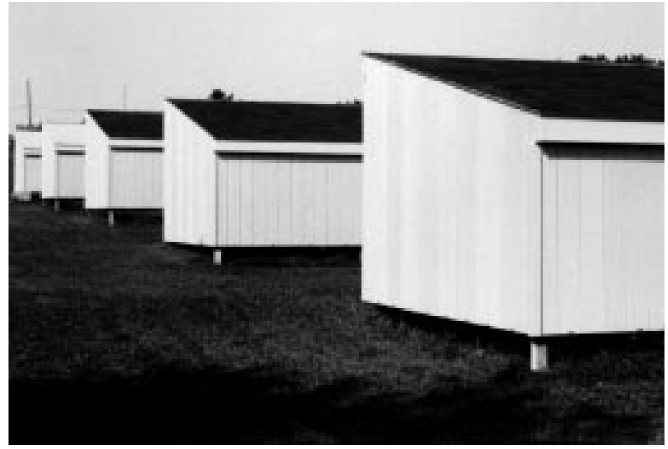

Figure 1—Outdoor field exposure chambers built near Madison, Wisconsin (latitide = 43.4° north). Each chamber holds 96 field exposure specimens. (M95 0057–24A)

Exposure Chambers

The 12-ft- (3.7-m-) wide by 16-ft- (4.9-m-) long, identical exposure chambers were constructed to simulate part of a typical multifamily attic/roof system in which model building codes sometimes allow FR-treated plywood roof sheathing. To achieve this type of construction, the chambers simulated in cross section the 1/8- to 3/8-span section of a 48-ft (14.6-m) span, 3:12 pitch roof system in both roof area and attic volume (Fig. 2). Each chamber was completely enclosed and kept unventilated. The four exterior walls were sheathed with 1/2-in.- (12-mm-) thick, 8-in.- (200-mm-) grooved Southern Pine siding attached to nominal 2- by 4-in. (standard 38- by 89-mm) wall studs. The exterior surfaces of each building were coated with one coat of primer and two top coats of latex solid-color stain or paint. The color of the stain or paint was light gray, almost white. The walls and the 5/8-in. (16-mm) plywood and nominal 2- by 10-in. (standard 38- by 235-mm) joist floor system of each chamber were not insulated. The chambers were roofed with CertainTeed XT-25 fiberglass roofing shingles that weighed 233 lb (106 kg) per square.[1] These shingles were essentially identical to those used in Champaign, Illinois, to study the behavior of attics constructed and ventilated in various ways (Rose 1992). White shingles were used on two chambers and black shingles on the remaining three chambers, which allowed us to address the effect of shingle color on thermal absorptivity. Because of the gentle slope of the test site, the north side of the chambers was approximately 12 in. (0.3 m) off the ground, whereas the south side was about 16 in. (0.4 m) off the ground.

In 1994, similar exposure chambers were constructed at the Mississippi Forest Products Laboratory at Mississippi State University in Starkville as part of an ongoing effort to relate temperatures in matched northern and southern U.S. roof systems (Barnes and others 1993). The conditions in the Mississippi study are expected to be more severe (that is, higher solar loading) than those in the Madison study. When available, the data from the Mississippi study will be integrated with field data from the Madison study.

Temperature Monitoring System

Two of the five field exposure chambers—one black-shingled chamber and one white-shingled—were instrumented with nine thermocouples variously located within the structure (Figs. 3 and 4). In each chamber, the first two thermocouples (T0 and T1) measured interior chamber temperature at 8 ft (2.43 m) and 5 ft (1.52 m) above grade, respectively. These thermocouples were centrally located along the back (north) wall. The third thermocouple (T2) measured exterior chamber temperature and was centrally located on the back wall. It was located 6 ft (1.83 m) above the grade. The fourth thermocouple (T3) was placed in the roof system below the roofing felt and attached by wood-fiber-based adhesive to the top veneer of the 3/4-in. (19-mm) plywood sheathing. This thermocouple was located high in the roof structure: at one-third of the rafter span approximately 4 ft (1.22 m) from the north (ridge) wall. The fifth thermocouple (T4) was similarly placed in the roof system below the roofing felt and attached to the top ply of the plywood sheathing, but it was located lower in the roof structure: at one-third of the rafter span approximately 4 ft (1.22 m) from the south (eave) wall. These two locations were selected because small roof systems such as this theoretically might not become as hot as large roof structures since air heats as it travels across the roof surface. Rose (1992) reported such a phenomenon affecting sheathing temperatures when comparing a 30-ft- (9.2-m-) wide system to a 42-ft- (12.8-m-) span system. However, we believe that

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

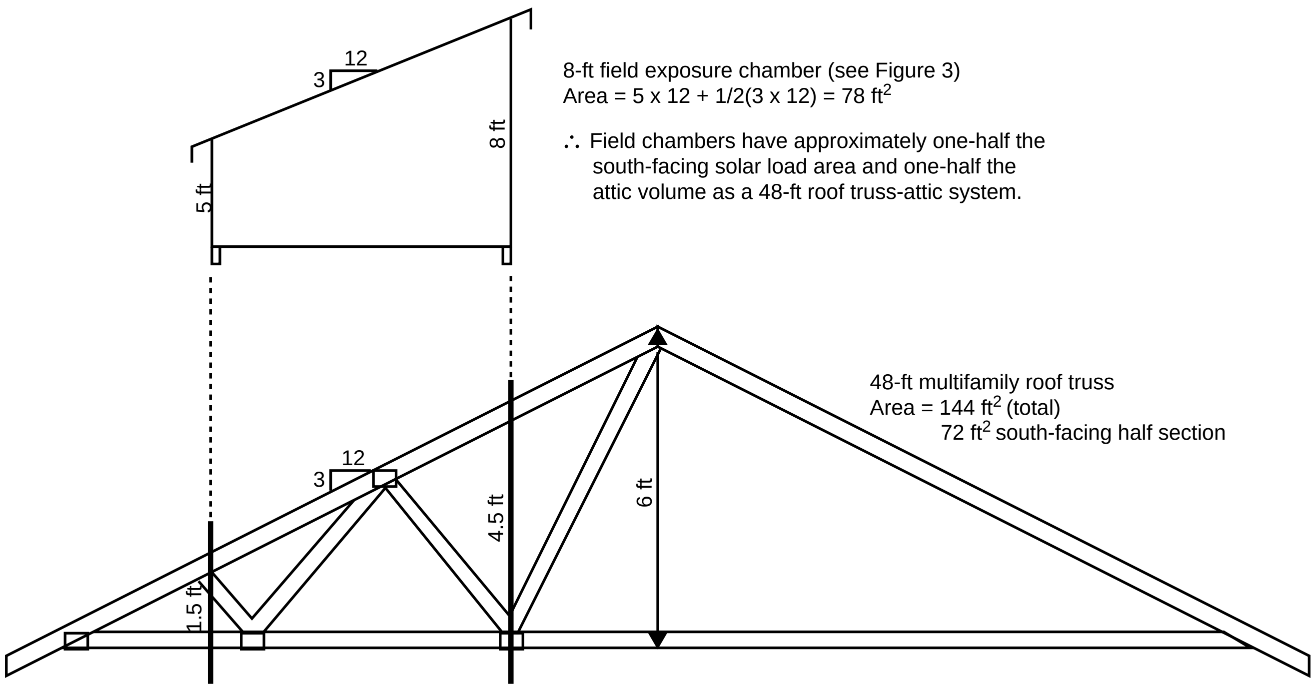

Figure 2—View of field exposure chamber in relation to roof truss of multifamily structure. Field chamber has approximately half the south-facing solar load area and half the attic volume as that of a 48-ft (14.6-m) roof truss–attic system. 1 ft^2 = 0.09 m^2.

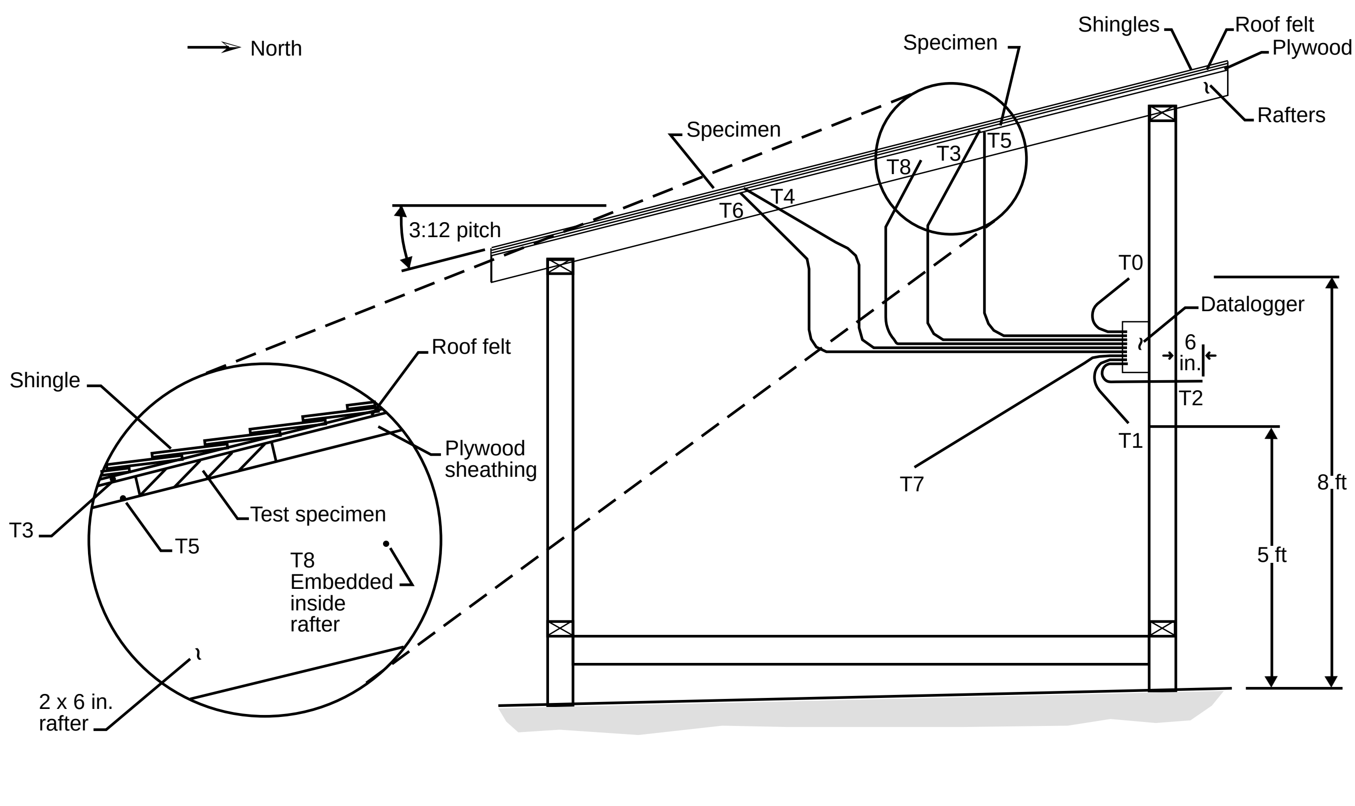

Figure 3—Schematic cross section of instrumented field exposure chamber showing location of thermocouples (T0–T8) and channels for datalogger/multiplexer.

overall the roof systems that we used were able to simulate thermal loading conditions within the small 4-in. (100-mm) by 22-in. (559-mm) plywood test specimens in a nearly identical manner to that experienced by full-sized 4-ft. (1.22-m) by 8-ft (2.44-m) sheets of treated roof sheathing.

The sixth thermocouple (T5) was attached to the bottom of the roof sheathing plywood, one-third of the rafter span from the north wall. Similarly, the seventh thermocouple (T6) was also attached to the bottom of the roof sheathing plywood, but one-third of the rafter span from the south wall. The eighth thermocouple (T7) was used as the external reference thermistor; it was a single channel identical to both buildings. This thermistor had a rated accuracy of ±0.4˚F (±0.2˚C) between –27˚F (–33˚C) and 120˚F (48˚C). The ninth thermocouple (T8) was located within the interior of the roof rafter/joist. Specifically, this thermocouple was inserted in the center of the 2- by 6-in. (38- by 140-mm) cross section at the midspan of the Western Hemlock rafter. The position of the T8 thermocouple allowed us to correlate rafter and sheathing temperatures directly to one another and eventually to solar load as monitored by the U.S. Weather Service at Truax Field in Madison (~8.5 mi [~13.5 km] east–northeast of the test site).

A Campbell–Scientific Model CR10 datalogger and a Model AM416, 32-channel multiplexer were used to collect and record the temperature data from the 17 thermocouple locations. The CR10 has a reported accuracy of 0.2 percent over the service temperature range of –67˚F (–55˚C) to 185˚F (85˚C). The datalogger and multiplexer were placed in a weather-sealed box inside the white-shingled chamber, on the east wall approximately 6-ft (1.83-m) above the floor. The datalogger–multiplexer system collected temperature data every 5 min for each exposure chamber; the datalogger was programmed to calculate and record hourly average temperatures. Each week, the hourly data were downloaded to disk with a laptop computer. The set-up of the datalogger–multiplexer system and a temporarily attached laptop computer is shown in Figure 5.

Results and Discussion

The fact that the field chambers were neither ventilated nor insulated means that the results reported here are truly indicative of only such construction. Furthermore, as mentioned earlier, a larger structure might theoretically experience higher temperatures, but to exactly what degree is unknown (Rose 1992). However, we believe that much practical information can be learned from studying the data generated by our field exposure study.

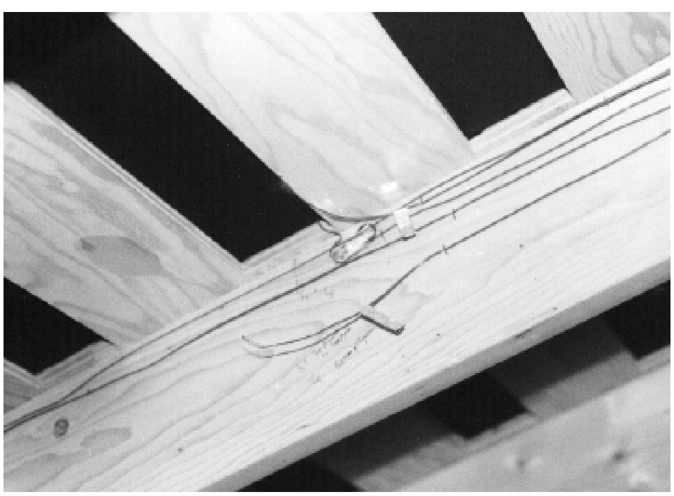

Figure 4—Placement detail of thermocouples for monitoring temperatures inside field exposure chamber and openings in sheathing plywood intended to accept sample specimens. All data were recorded with field exposure specimens in place. (M95 0057–22A)

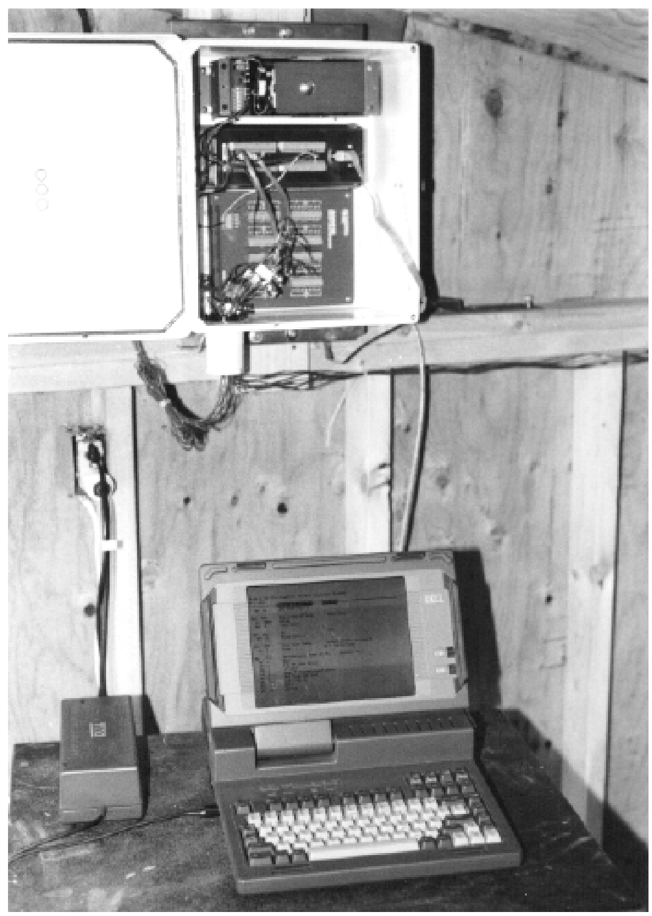

Figure 5—Set-up of datalogger–multiplexer, temporarily attached to downloadable, portable computer system. (M95 0057–21A)

Top-of-sheathing and bottom-of-sheathing temperatures were monitored at the one-third and two-third roof span locations midway between the eaves and the ridge (thermocouples T3–T6). The difference in recorded hourly temperatures between the top-of-plywood locations (thermocouples T3 and T4) and between the bottom-of-plywood locations (thermocouples T5 and T6) seldom exceeded 2˚F (1˚C). This small difference in temperature across the span of the structure may be indicative of the short span or lack of ventilation. Rose (1992) found that increased ventilation with pitched, cathedral ceiling systems increased this across-the-span temperature differential. However, subsequent results comparing vented and unvented flat-roof systems showed few differences in sheathing temperature between the eaves and the ridge (Rose n.d.). Because of the small temperature differential between the two sets of midspan locations in our study, temperature readings for each set of locations were averaged; this average hourly value is henceforth reported. The actual number of hours at given temperatures for the black-shingled and white-shingled exposure chambers for each 12-month period between October 1991 and September 1994 are shown in Tables 1 to 6. Figures 6 to 11 depict these data for three locations in the chambers. In these figures, the abscissa shows the "exceedence temperature," which is defined as the range between some minimum temperature limit and the next higher exceedence temperature limit; the ordinate is the number of hours that recorded temperatures at that location went beyond the exceedence range. Average values of the 3-year test period are given in Figure 12; direct comparisons between the years are given in Figure 13.

Comparison of Black- and White-Shingled Chambers

Note that for most recorded locations, the black-shingled roofs were generally 10°F to 15°F warmer than identical white-shingled roofs on sunny days (Figs. 14 and 15). However, during the evening, the black-shingled roofs also tended to lose heat faster than did the white-shingled roofs. In obtaining equilibrium with ambient outdoor temperature, both black-shingled and white-shingled roofs generally experienced similar nighttime temperature profiles. Also, note that on average over the 3-year monitoring period, the plywood of the black-shingled roof systems was annually subject to about 191 h of exposure to 120°F–130°F (49°C–54°C), 116 h of 130°F–140°F (54°C–60°C), 46 h of 140°F–150°F (60°C–66°C), 8 h of 150°F–160°F (66°C–71°C), and 2 h above 160°F (71°C) (Tables 1–3). Meanwhile, the white-shingled roofs were annually subject to about 63 h of exposure to 120°F–130°F (49°C–54°C), 9 h of 130°F–140°F (54°C–60°C), and 2 h of 140°F–150°F (60°C–66°C) (Tables 4–6).

Two points are apparent. First, shingle color or, more appropriately, radiant absorptivity of the shingle was a predominant factor in dictating peak roof sheathing temperatures. Second, the cumulative histograms of top-of-plywood sheathing temperature (Figs. 6–11) consistently show a saddle between 90°F (32°C) and 120°F (49°C), which may represent the transition from ambient to radiant heating/cooling.

Difference in Yearly Temperature Histories

A comparison of outdoor temperature histories from 1991 through 1994 is informative (Figs. 6–11, Tables 1–6). When studying the winter weather/exposure patterns, note that based on a comparison of the colder periods of outside ambient temperature, the winters of 1991–92 and 1992–93 were quite similar in cumulative and minimum cold temperatures (Tables 1–6). Both of these winters were considered average to slightly colder than average. However, the winter of 1993–94 was considerably colder than normal, which became apparent when comparing the 3-year data. We also noted that the effect of snow cover could often be evaluated by simply monitoring the top-of-plywood temperatures. When snow cover was present, especially a new snow cover on a previously snow-free roof with either black- or white-shingled chambers, we repeatedly observed that the top-of-plywood temperature data would hover very near 32°F (0°C). We assume that as snow melts and refreezes, it acts as a phase-changing medium that stabilizes the sheathing temperatures. Most importantly, we noted that trends and/or fluctuations in this top-of-plywood temperature were controlled during snow-covered periods by the air temperature in the interior attic space, which, in turn, dictated the temperature at the bottom of the plywood sheathing. In other words, the snow cover acted like an insulative blanket in which thermal loads on the roof sheathing were dictated from inside-to-outside heat flux rather than the normal outside-to-inside flux.

Study of the summer temperature histories readily shows that the summer of 1994, which was generally considered average to slightly warmer than average, was much warmer than either the previous summers (Figs. 6–11 and 13). The summer of 1992 was considered cooler than normal (Figs. 6 and 7), and the summer of 1993, considerably cooler than normal (Figs. 8 and 9). In fact, during the summer of 1993, we did not record an exterior temperature above 89°F (32°C), and U.S. Weather Service records indicate that this summer was the second coolest summer recorded in Madison, Wisconsin, in the 20th century. Nevertheless, during the summers of 1992 and 1993, short warm periods did occur (Fig. 14). In June of 1992, when exterior temperatures exceeded 90°F (32°C) for several consecutive

Table 1—Temperatures in black-shingled exposure chamber, October 1991–September 1992

Temp	Time (h) at given temperature at various locations				
	Chamber		Plywood		
(°F)[a]	Inside	Outside	Top	Bottom	Rafter
–20	9	—	15	12	14
–10	41	42	73	54	45
0	162	172	185	172	156
10	421	498	438	416	407
20	1,057	1,103	1,086	1,080	1,063
30	1,693	1,870	1,572	1,612	1,646
40	1,236	1,228	1,209	1,230	1,240
50	1,203	1,296	1,118	1,161	1,160
60	1,250	1,559	1,015	1,132	1,194
70	707	812	524	665	716
80	484	165	391	417	442
90	365	12	305	358	382
100	115	1	241	274	238
110	12	—	218	146	54
120	—	—	194	28	—
130	—	—	115	1	—
140	—	—	52	—	—
150	—	—	6	—	—
160	—	—	1	—	—

[a]$T_C = (T_F - 32)/1.8$.

Table 2—Temperatures in black-shingled exposure chamber, October 1992–September 1993

Temp	Time (h) at given temperature at various locations				
	Chamber		Plywood		
(°F)	Inside	Outside	Top	Bottom	Rafter
–20	4	1	10	7	6
–10	54	49	112	87	67
0	228	244	221	212	216
10	520	659	558	537	509
20	1,112	1,268	1,074	1,106	1,088
30	1,703	1,702	1,639	1,662	1,701
40	1,018	956	951	981	983
50	1,102	1,248	1,063	1,095	1,072
60	1,175	1,453	1043	1,116	1152
70	868	971	586	729	818
80	532	211	471	465	518
90	358	—	293	386	434
100	88	—	288	282	170
110	11	—	243	87	41
120	—	—	162	25	5
130	—	—	84	3	—
140	—	—	27	—	—
150	—	—	6	—	—
160	—	—	3	—	—

Table 3—Temperatures in black-shingled exposure chamber, October 1993–September 1994

Temp	Time (h) at given temperature at various locations				
	Chamber		Plywood		
(°F)	Inside	Outside	Top	Bottom	Rafter
–20	111	109	147	128	111
–10	156	219	164	169	167
0	277	329	284	261	268
10	561	572	646	622	572
20	834	872	805	832	827
30	1,413	1,531	1,373	1,382	1,374
40	994	1,073	921	956	970
50	1,119	1,178	1,079	1,138	1,100
60	1,290	1,596	1,058	1,141	1,234
70	796	970	581	701	773
80	574	279	406	489	543
90	422	31	305	398	455
100	178	—	303	327	286
110	21	—	246	171	69
120	2	—	218	41	10
130	—	—	148	3	—
140	—	—	60	—	—
150	—	—	13	—	—
160	—	—	2	—	—

Table 4—Temperatures in white-shingled exposure chamber, October 1991–September 1992

Temp	Time (h) at given temperature at various locations				
	Chamber		Plywood		
(°F)	Inside	Outside	Top	Bottom	Rafter
–20	8	—	16	11	11
–10	42	42	74	50	47
0	162	170	196	178	160
10	430	508	461	429	417
20	1,079	1,099	1,152	1,077	1,085
30	1,735	1,870	1,622	1,683	1,691
40	1,250	1,224	1,233	1,258	1,260
50	1,219	1,273	1,152	1,186	1,202
60	1,279	1,567	1,068	1,230	1,233
70	753	823	604	684	723
80	509	167	392	441	470
90	257	14	293	363	362
100	33	—	246	150	89
110	—	—	178	17	7
120	—	—	65	—	—
130	—	—	5	—	—
140	—	—	—	—	—
150	—	—	—	—	—
160	—	—	—	—	—

Table 5—Temperatures in white-shingled exposure chamber, October 1992–September 1993

	Time (h) at given temperature at various locations				
Temp	Chamber		Plywood		
(°F)	Inside	Outside	Top	Bottom	Rafter
–20	4	1	11	6	6
–10	53	50	116	75	65
0	222	239	223	220	215
10	532	665	586	528	522
20	1,158	1,276	1,131	1,144	1,131
30	1,719	1,701	1,705	1,695	1,714
40	1,004	961	958	1,011	995
50	1,129	1,227	1,112	1,123	1,115
60	1,249	1,463	1,080	1,155	1,187
70	877	970	669	820	875
80	547	227	385	504	541
90	238	—	346	367	326
100	43	—	279	108	78
110	—	—	126	23	10
120	—	—	40	1	—
130	—	—	10	—	—
140	—	—	3	—	—
150	—	—	—	—	—
160	—	—	—	—	—

Table 6—Temperatures in white-shingled exposure chamber, October 1993–September 1994

	Time (h) at given temperature at various locations				
Temp	Chamber		Plywood		
(°F)	Inside	Outside	Top	Bottom	Rafter
–20	110	111	152	119	112
–10	160	216	167	168	166
0	275	317	317	279	277
10	577	582	658	594	577
20	853	878	859	867	860
30	1,426	1,523	1,405	1,407	1,403
40	1,015	1,065	950	974	980
50	1,155	1,187	1,138	1,150	1,161
60	1,315	1,576	1,110	1,238	1,257
70	843	992	621	776	832
80	608	282	427	516	557
90	354	30	338	413	405
100	58	—	308	224	158
110	2	—	211	32	13
120	—	—	84	2	1
130	—	—	12	—	—
140	—	—	2	—	—
150	—	—	—	—	—
160	—	—	—	—	—

days and afternoon wind speed at Truax Field in Madison was reported at 5–10 mi/h (8–16 km/h), the white-shingled chamber reached its maximum temperatures when rafter temperatures exceeded 110°F (43°C) and top plywood temperature exceeded 135°F (57°C) (Fig. 14, Table 5). During the same week in 1992, rafter temperatures in the black-shingled chamber approached 120°F (49°C) and the top plywood temperature exceeded 150°F (66°C) (Fig. 14, Table 2). However, that was not the maximum plywood roof sheathing temperature for 1992. The peak happened a few weeks later, during a 3-day period when daily exterior temperatures only reached 85°F to 88°F (29°C to 31°C) but Truax Field wind speed was ≤ 5 mi/h (≤ 8 km/h), at which time the top plywood temperatures of the black-shingled chamber exceeded 150°F (66°C) each day and reached their annual maximum of 161°F (72°C) (Table 1). This indicates that solar load and wind speed can be as important as outdoor temperature.

Temperature Trends

Over the 3-year monitoring period, the highest daily and weekly temperatures were recorded in June 1994 after the longest continuous hot-spell in Madison, Wisconsin—from June 13 through June 26 (Fig. 15). During that period, the sky was almost continuously clear from June 13–19 and from June 21–22. Figure 15 reveals several temperature trends.

First, note that from June 13 through June 17, daily high temperatures peaked between 90° and 96°F (32°C and 36°C), with warmest outside (shade) hourly temperatures recorded on both June 16 and 17. The highest hourly temperature over the 3-year period—168°F (77°C)—was recorded on June 17 between 1:00 and 2:00 p.m. for the top surface of the plywood roof sheathing of the black-shingled chamber. The highest temperatures recorded at the bottom of the plywood sheathing and for the rafter were recorded 1 h later—137°F (58°C) and 129°F (54°C), respectively. At that time for the white-shingled chamber, the top surface of the plywood roof sheathing reached 147°F (64°C), the bottom of the plywood sheathing 127°F (53°C), and the rafter 120°F (49°C).

Second, note that on June 22, chamber temperatures were nearly identical to the outside temperature of 60°F–70°F (16°C–21°C) throughout the day as a result of continuous rain.

Finally, note the modest drop in the mid-day recorded temperatures on June 19 and again on June 23 and 24 caused by the brief occurrence of late-afternoon clouds and light rain. This weather pattern was verified with U.S. Weather Station records at Truax Field.

Note that there is a slow but consistent trend of rising daily maximum temperatures for both black- and white-shingled chambers. This trend could be explained in several ways. One explanation could be as simple as diminishing wind speed, which in turn results in less convective heat loss. Another could be a slow reduction in upper atmosphere cloud cover (high cirrus). Finally, the entire roof system might be beginning to store energy. However, this last possibility is unlikely because daily low temperatures do not exhibit a corresponding trend of raising temperatures.

Overall it is interesting that the annual time–temperature histories (Tables 1 to 6) are similar to the average number of hours reported for similar ventilated and unventilated roof structures (Rose 1992) and those predicted using roof temperature models (ASTM 1988, APA 1989). This confirms that whereas internal attic air temperatures may be strongly influenced by ventilation and insulation, the temperatures to which roof-sheathing plywood and roof-truss lumber are subjected appear to be primarily controlled by solar gain. Thus, our decision to limit attic ventilation or attic insulation appears justified in regard to our objective of monitoring peak roof-sheathing temperatures and cumulative roof-sheathing temperature histories. However, this result should not be taken as counterindicative to the benefits of attic ventilation in controlling attic air temperature, relative humidity, and wood moisture content.

Concluding Remarks

The plywood roof sheathing of black-shingled field exposure chambers was subjected to significantly more time at temperatures above 120˚F (49˚C) than the roof sheathing of white-shingled chambers. On sunny days, the top ply of plywood roof sheathing under black shingles was 10˚F to 15°F (5˚C to 8˚C) warmer than that of identical white-shingled roof chambers. However, after dark, the black-shingled roof temperatures were similar to those of white-shingled roofs. The maximum temperatures recorded in our 3-year study for black-shingled roofs were 168˚F (76˚C), 137˚F (58˚C), and 129˚F (54˚C) for the top ply, bottom ply, and internal rafter temperatures, respectively. The maximum temperatures recorded for the white-shingled roofs were 147˚F (64˚C), 127˚F (53˚C), and 120˚F (49˚C) for the top ply, bottom ply, and internal rafter temperatures, respectively. The cumulative annual temperature histories reported in this paper for unventilated and uninsulated roof systems compared reasonably well with those reported for similar sloped and shingled roof structures located in central Illinois in which ventilation and insulation were specifically controlled. This confirms that the roof-sheathing plywood and roof-truss lumber temperatures, which are the primary factors influencing thermal degrade of fire-retardant-treated materials, are primarily controlled by solar gain rather than attic ventilation or attic insulation. However, the effect of moisture content was not evaluated nor was moisture controlled by attic ventilation.

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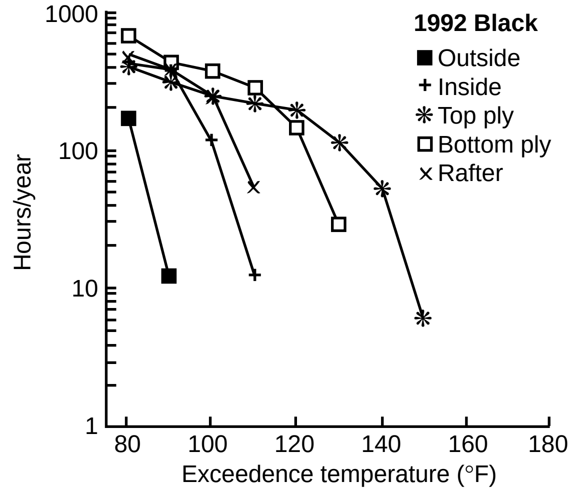

Figure 6—Number of hours that recorded temperatures at specified locations went beyond the exceedence temperature in black-shingled exposure chamber in 1992. Exceedence temperature is the range between some minimum temperature limit and next higher exceedence temperature limit. Outside and inside refer to exterior and interior temperatures of exposure chamber. Top plywood and bottom ply refer to temperatures of plywood sheathing at respective places. $^{a}T_C = (T_F – 32)/1.8$.

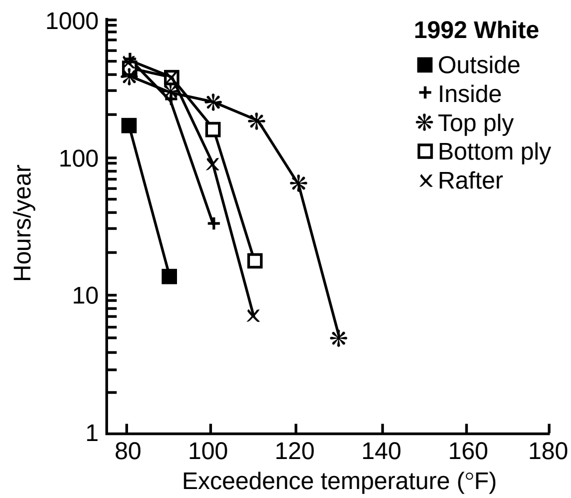

Figure 7—Number of hours that recorded temperatures at specified locations went beyond the exceedence temperature in white-shingled exposure chamber in 1992.

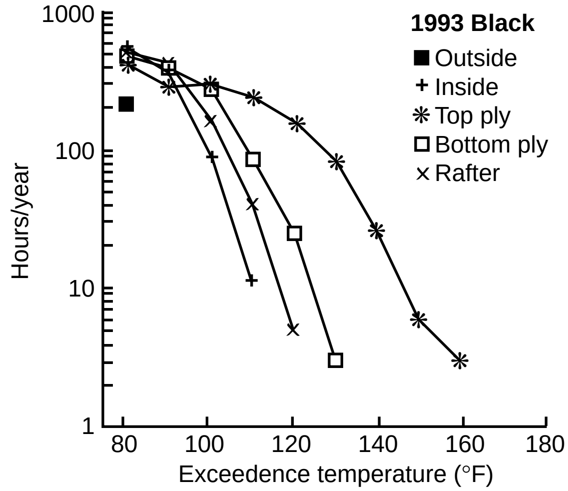

Figure 8—Number of hours that recorded temperatures at specified locations went beyond the exceedence temperature in black-shingled exposure chamber in 1993.

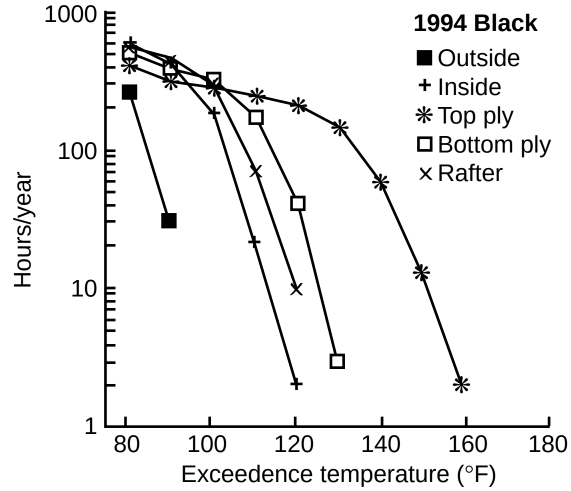

Figure 10—Number of hours that recorded temperatures at specified locations went beyond the exceedence temperature in black-shingled exposure chamber in 1994.

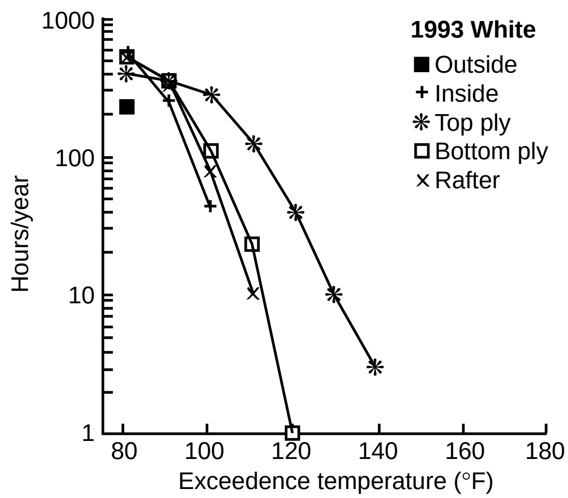

Figure 9—Number of hours that recorded temperatures at specified locations went beyond the exceedence temperature in white-shingled exposure chamber in 1993.

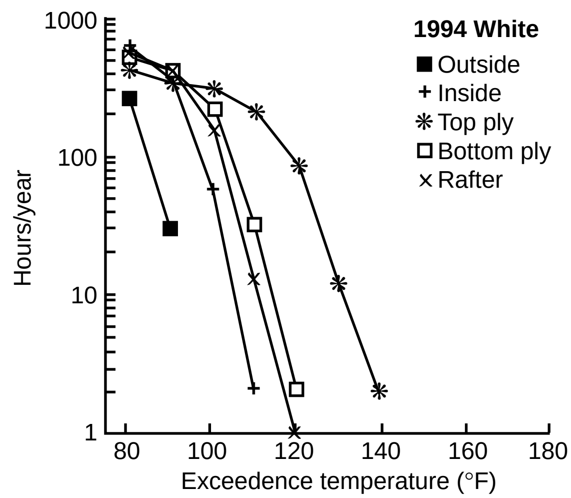

Figure 11—Number of hours that recorded temperatures at specified locations went beyond the exceedence temperature in white-shingled exposure chamber in 1994.

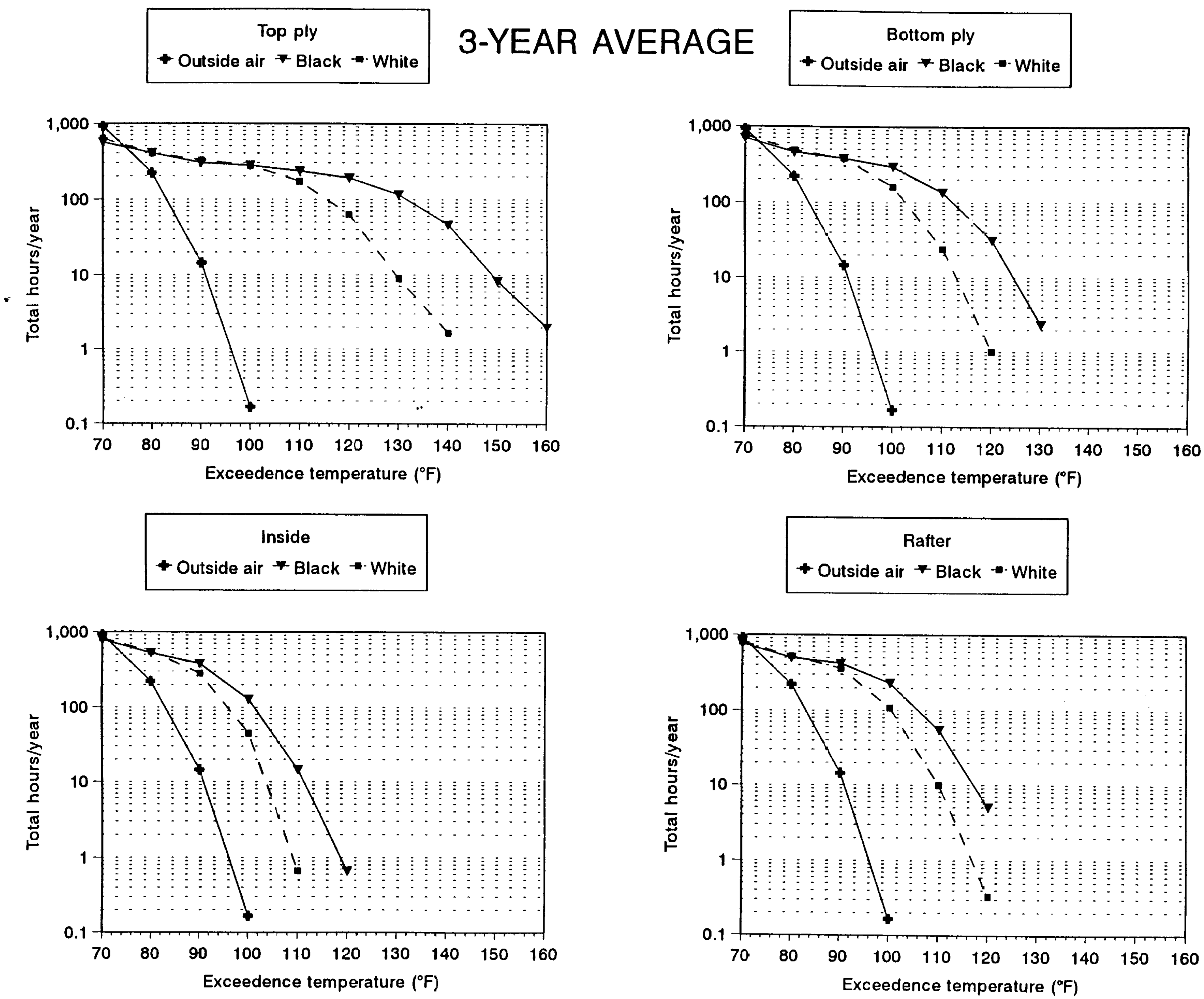

Figure 12—Three-year averages for time that recorded temperatures at specified locations went beyond the exceedence temperature in black- and white-shingled exposure chambers.

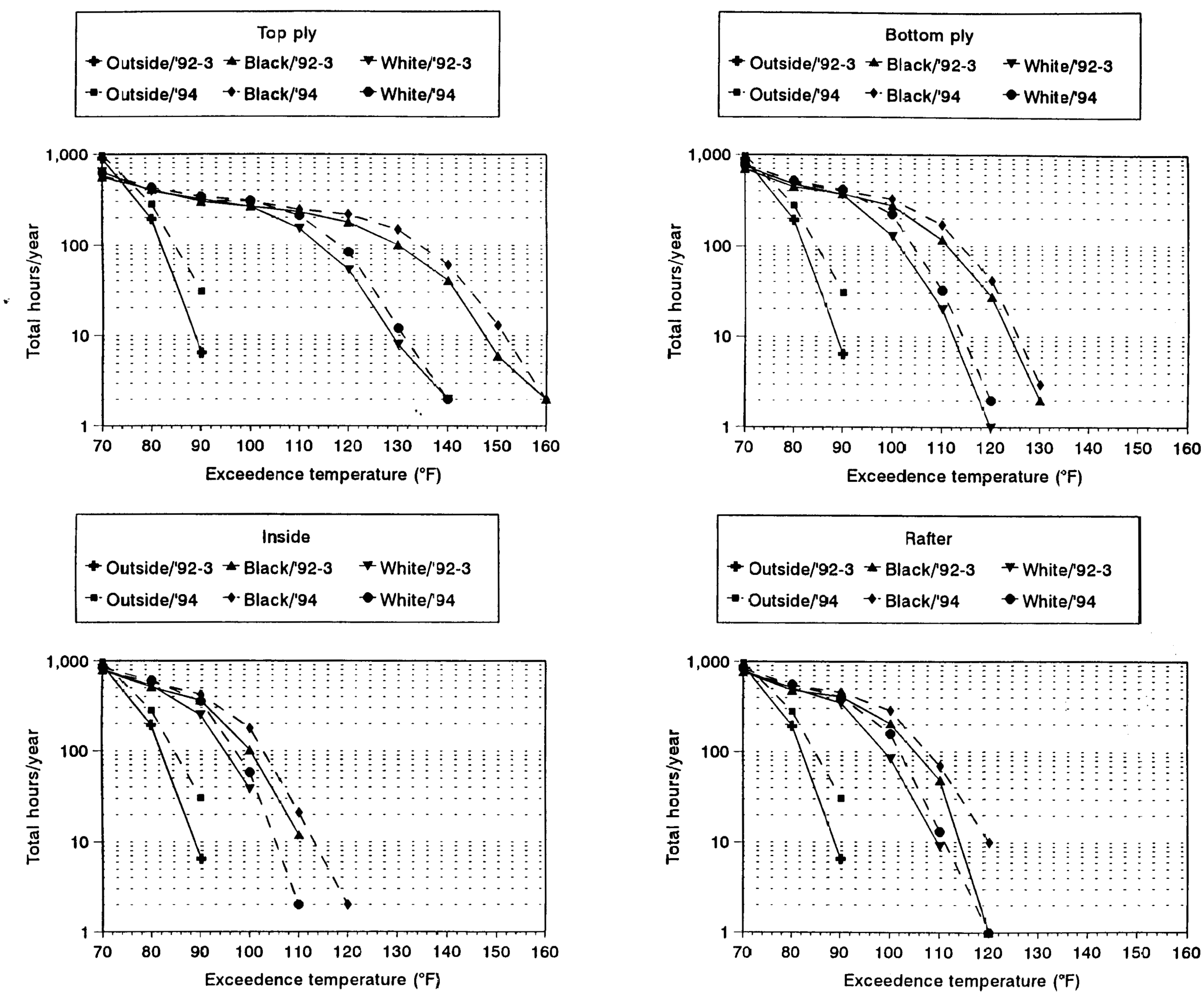

Figure 13—Comparison of time that recorded temperatures at specified locations went beyond the exceedence temperature in black- and white-shingled exposure chambers in 1993 and 1994.

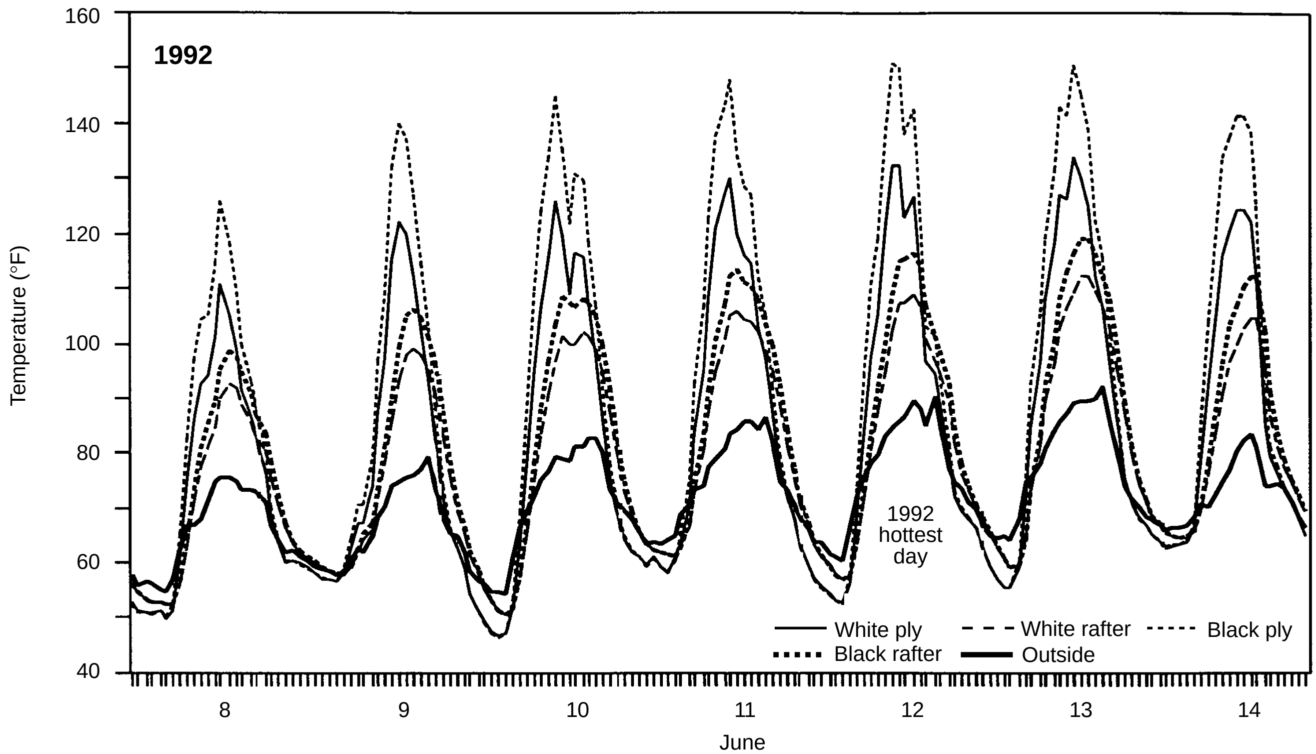

Figure 14—Comparison of temperature histories in specified locations in black- and white-shingled exposure chambers in 1992.

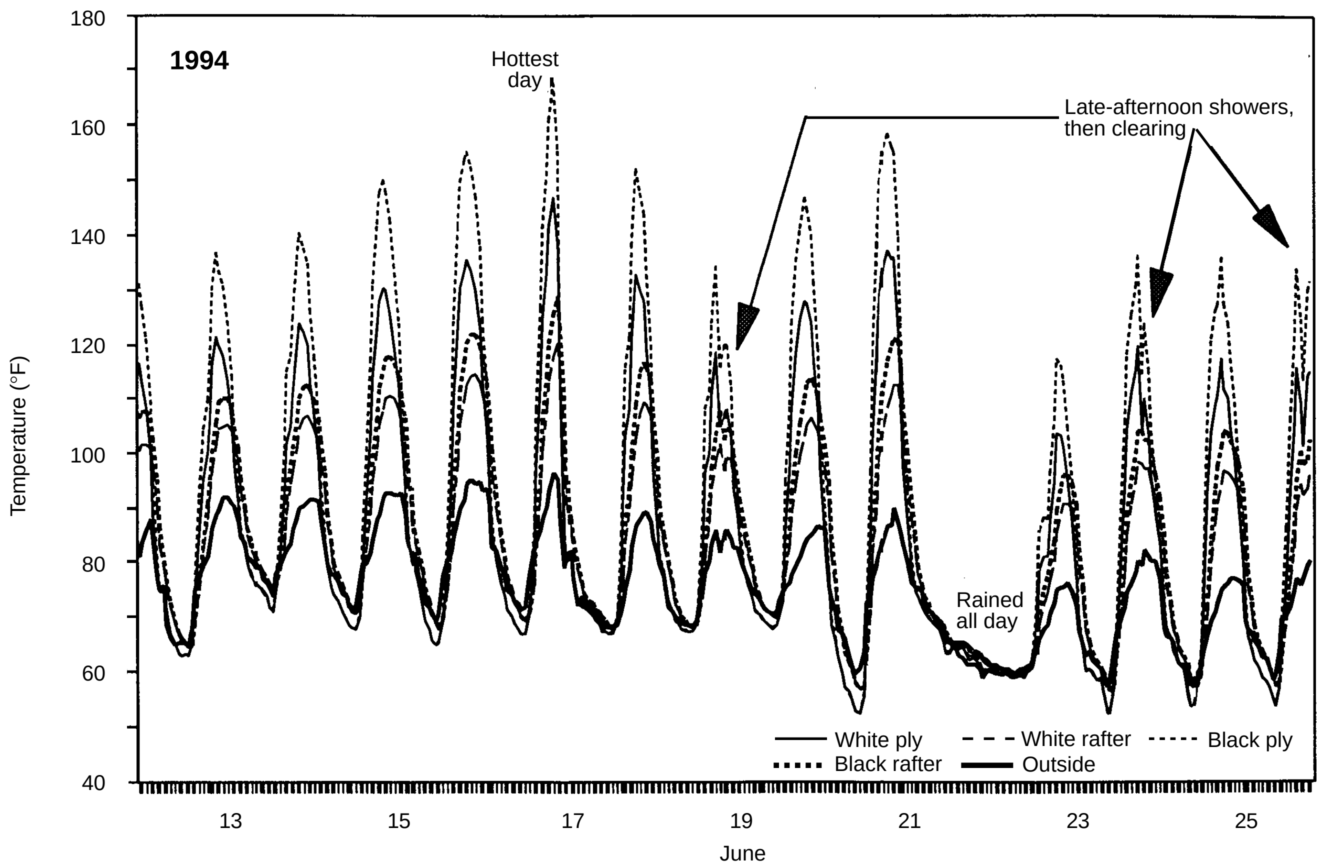

Figure 15—Comparison of temperature histories in specified locations in black- and white-shingled exposure chambers in 1994.