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Durability of Hardboard Lap Siding

Performance in Laboratory Testing and in Long-Term Exterior Exposure

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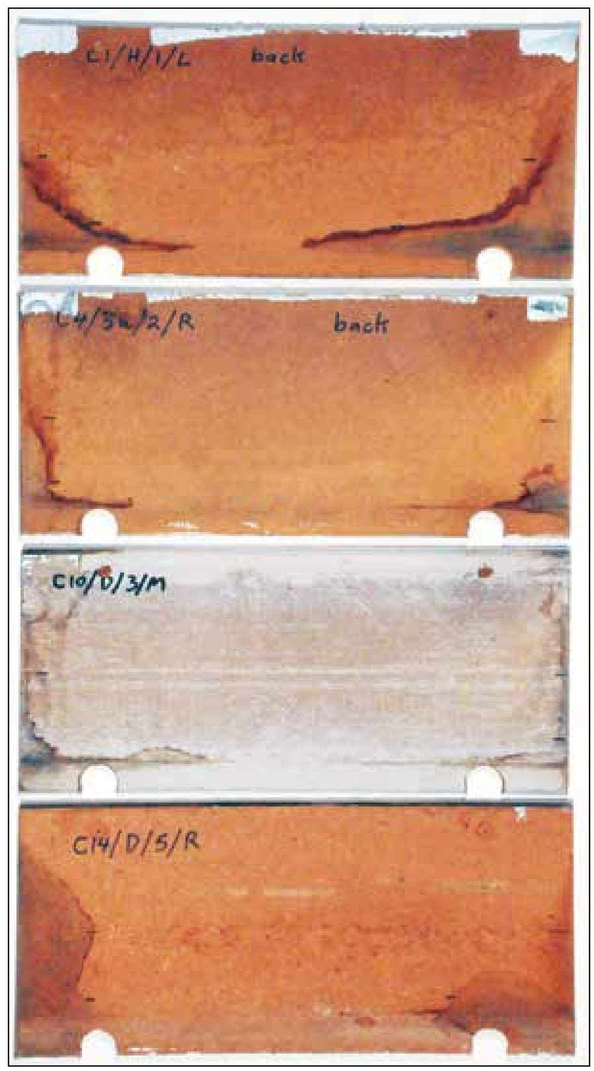

Abstract

This paper describes a study that was undertaken to evaluate the degree of correlation between in-service performance of hardboard siding and its performance in the industry standard test procedure for "weatherability of substrate." The study included 13 different hardboard sidings: 6 noncommercial boards and 7 commercial products. All manufacturing plants operating in the United States in 1996–1997 were represented in the study. Twenty replicate specimens of each of the 13 different boards were exposed on the south side of an unconditioned building near Madison, Wisconsin, for 155 months (almost 13 years). Although the climate at the exposure site was less challenging with regard to rainfall or decay hazard than most locations in the eastern United States, paint coating on test specimens was only about half as thick as recommended. Two failure modes were observed in service, drip-edge paint cracking and edge welting, although paint condition on board faces remained essentially perfect throughout the exposure period. With regard to the two observed failure modes, substantial differences were observed among the 13 sidings. Relative frequency of the two failure modes was related to residual thickness swelling (RTS) value of the board, as identified by the substrate weatherability test procedure. Lower RTS values were associated with lower relative frequency of failure and lower relative frequency of more intense failure. In general, there was no "plateau" value below which further reductions in RTS were not associated with greater relative frequency of improved in-service performance.

Keywords: Hardboard siding, long-term exposure, durability, edge welt, drip edges

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Acknowledgments

This study was funded by the U.S. Department of Housing and Urban Development. Additional support was provided by the American Hardboard Association. Anton TenWolde (retired from FPL) played a lead role in design of the study. Gerry Laughinghouse, formerly of Georgia-Pacific Corporation, assisted in developing the study, and coordinated production of noncommercial board. Harry Warren (retired from Masonite Corporation) and Louis Wagner (formerly with the American Hardboard Association) provided advice and coordinated the acquisition of commercial board. Vyto Malinauskas (deceased) prepared the test building for installation of specimens and served as data recorder for inspections conducted during the early years of exposure. Robert Munson assumed the role of helper/recorder for the inspector from 2002 through 2007. Alex Wiedenhoeft performed the microscopic inspections of board back surfaces that identified that fungal colonizations had occurred. Flavio Ruffinato (visiting scholar at FPL, and PhD student at the University of Turin) produced the micrographs shown as Figures 7a, 7b, and 12. David Marr (formerly with FPL) and Neil Gribbins performed density distribution measurements, which yielded data presented in Table 4. Chris Hunt produced micrographs from which paint film thicknesses were measured and provided the lead author with information that permitted him to download and use the ImageJ software.

In Memorium

Charlie Carll passed away shortly before the publication of this paper. His coauthors acknowledge his strong leadership in this research and recognize that his death represents a great loss to his family, his friends, and the wood research community.

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Durability of Hardboard Lap Siding

Performance in Laboratory Testing and in Long-Term Exterior Exposure

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Background

During the 1990s, researchers at the USDA Forest Products Laboratory (FPL) undertook two studies concerning performance of hardboard lap siding. The first study involved exposure of hardboard lap siding on test buildings in southern Florida for a period of 29 months (Carll and others 2000). The study was intended to evaluate the effectiveness of a Local Acceptance Standard (LAS) promulgated by the Department of Housing and Urban Development (HUD) that would have required factory finishing of hardboard siding and priming of all surfaces (including the back surface). All siding in that study was produced at one manufacturing plant and had physical properties that were substantially better than required by the industry standard for hardboard siding (AHA 1990).[1] Moisture content of the siding remained low over the course of the exposure period, regardless of whether the siding was site-finished or factory-finished or whether it was primed on its back surface. The siding remained in excellent condition, reflecting its consistently low in-service moisture content. No conclusions that might have been generically applicable to hardboard siding could be drawn from the study, because the study had included siding from only one manufacturing plant. Commercial hardboard siding available during the late 1980s and early 1990s showed substantial variation in physical properties (Biblis 1989, 1991). A second study, which addressed performance of hardboard siding from all manufacturing plants in the United States (Carll and TenWolde 2004) was therefore initiated in 1997.

The American National Standard for Hardboard Siding, in its three most recent editions (AHA 1990, 1998; CPA 2006), outlined a number of test procedures for evaluation of the product and specified acceptance criteria related to the test procedures. Keplinger and Waldman (1998) and Baldwin (1988) indicated that when there are durability problems with hardboard siding, irreversible (or "residual") thickness swelling is frequently a contributing factor to, or a cause of, problems. This suggested that the procedure in the American National Standard that involves measurement of residual thickness swell (RTS), referred to as the "weatherability of substrate" test, would predict performance in service. As of the late 1990s, however, the literature did not contain evidence that performance in the substrate weatherability test procedure correlated with performance in service.

A main objective of the Carll and TenWolde (2004) study was to evaluate the degree of correlation between performance in the industry standard test procedure for "weatherability of substrate" and performance in use. The study involved laboratory testing and field exposure of a variety of hardboard sidings with a wide range of residual thickness swelling. Painted siding specimens, matched to unpainted laboratory test specimens, were installed on a test building (exterior exposure without additional water spray) and on two test fences that were sprayed with water for 1 h once a day during warm months (accelerated exterior exposure). The exposure site was FPL's Valley View test site, just west of Madison, Wisconsin. Results from the 39-month accelerated exterior exposures were reported (Carll and TenWolde 2004). RTS, as measured by the "weatherability of substrate" test procedure, proved to be a good indicator of the likelihood of three modes of problematic performance on the spray fences: edge welting, mildew growth, and paint cracking on drip edges. Each of these problematic performance modes was moisture related. The exposure period for specimens placed on the test building (nonaccelerated exterior exposure) was intended to be a decade or slightly more. At the time of publication of Carll and TenWolde (2004), the exposure period had been substantially less than a decade, so data for specimens on the test building were, for the most part, not reported. The exposure period reached 10 years in September 2007 and was continued until August 2010.

The present paper addresses performance of specimens on the test building over their approximately 13 years of exposure, in other words, the completion of the study initiated in 1997. Among other things, it reports on correlation between in-service performance of specimens and their performance in laboratory testing. It covers, in some detail, the two problematic behaviors ("failure modes") that were observed during exposure.

[1]The study was performed under a Sponsored Research and Development Agreement between the USDA Forest Service, Forest Products Laboratory, and a manufacturer of hardboard siding. The manufacturer operated more than one plant, but produced siding for the Florida market at only one of their plants.

Objectives

The study objectives, outlined by Carll and TenWolde (2004), were (1) to examine to what extent performance in the industry standard test procedure for "weatherability of substrate" correlated with siding performance in use, (2) to determine if change in the acceptance criterion for "substrate weatherability" in the American National Standard was justified, and (3) to examine to what degree results from other laboratory tests correlated with siding performance in use. The acceptance criterion in the American National Standard for substrate weatherability was changed in 2006, with maximum allowable value for RTS lowered from 20% to 17% (CPA 2006). This change was based on results from the part of the study involving accelerated exposure (Carll and TenWolde 2004) that indicated that RTS was an imperfect but nonetheless useful predictor of performance characteristics on test fences and that the likelihood of certain problematic behaviors ("failure modes") was noticeably greater when RTS exceeded 17%. In light of the 2006 revision of the American National Standard, the second objective for the remaining phase of the study has been revised. The revised objective is to evaluate the now-current 17% RTS criterion value in the industry standard. A fourth study objective has been added, which is to identify prevalence of different "failure modes" in long-term exterior exposure and to document the patterns in which they develop.

Approach and Methodology

The approach of the study and the methodologies it employed were described previously (Carll and Ten Wolde 2004). Nevertheless, essential elements of the study's approach and methods are reiterated here. Materials in the study included six noncommercial hardboard sidings and seven commercial hardboard sidings. One oriented strandboard (OSB) siding was also included as a reference material. All U.S. hardboard manufacturing plants producing hardboard siding in 1996–1997 were represented in the study.

Siding Classes

The 13 different hardboard sidings in the study were each assigned a "class" number. In the case of noncommercial boards, class number was based on level of RTS observed in preliminary testing. In the case of commercial boards, class number was based on the order in which shipments were received at FPL from production plants.

The six noncommercial classes of siding were selected from different lots of board produced for the study at an industrial plant. One of the lots was produced using the plant's normal pressing procedures and was thus similar to commercial board produced at the plant. Three additional lots were specially produced at lower than usual press temperatures and shorter press times to yield test materials that exhibited a wide range of properties, in all cases inferior to those of boards produced using the plant's normal pressing procedures. The noncommercial boards were shipped to FPL as unprimed 4- by 8-ft (1.2- by 2.4-m) sheets. At FPL, the sheets were sawn into 8-ft (2.4-m) by 8-in.- (0.2-m-) wide strips of lap siding; these siding strips therefore did not have shaped drip edges. In preliminary testing, RTS value within individual strips was found to be largely predictable based on production lot and position of the strip from within the 4- by 8-ft sheet. The six classes of noncommercial board were thus based on production lot and strip position.

Each of the seven commercial classes of hardboard siding was produced at a different production plant. The commercial hardboards were shipped to FPL as factory-primed strips of nominally 8-in.- (0.2-m-) wide lap siding with beveled or slightly rounded drip edges, which had been shaped prior to priming. All the hardboard sidings (commercial and noncommercial) had flat smooth (not textured) front surfaces.

Because OSB siding was, at the time of study initiation, not readily available as lap siding, 8-in.-wide by 8-ft-long strips of siding were sawn at FPL from 4- by 8-ft (1.2- by 2.4-m) sheets of panel siding obtained from a lumber retailer. The OSB siding had an embossed (textured) face. It contained zinc borate, which was confirmed by atomic emission spectroscopy. The OSB siding was assigned a class number of 9, reflecting that it was received at FPL after two of the commercial hardboards (classes 7 and 8) but before five of the commercial hardboards (classes 10 to 14).

Specimen Selection and Preparation

Twenty 8-ft-long strips were selected from each "class" (a total of 260 hardboard siding strips and 20 OSB siding strips) to provide specimens for laboratory testing and for outdoor exposure. Laboratory testing included substrate weatherability (residual thickness swell), edge water absorption, and water vapor sorption. The cutting diagram for specimens obtained from the selected strips was presented as figure 3 in Carll and TenWolde (2004). Three specimens for exterior exposure were obtained from each strip, two for accelerated exposure on spray fences and one for long-term exposure on a test building.

Specimens for exterior exposure were brush painted with two thin coats of satin exterior latex paint. On the commercial hardboards, the latex paint was applied over the factory primer. On the noncommercial hardboards, which were not factory primed, the latex paint was applied over brush-applied alkyd primer. The alkyd primer was from the same manufacturer as the latex topcoat. It was compatible with the topcoat and recommended by the paint manufacturer for use on hardboard that had not been factory primed. The OSB siding had a resin-impregnated paper face, intended to serve as a topcoat base and was painted with two coats of the satin latex paint without priming. Average spread rate for the combined two coats of latex paint was 387 ft^2/gal (9.5 m^2/L) on the hardboard and 267 ft^2/gal (6.6 m^2/L) on the OSB. The solids content of the satin exterior paint was approximately 37% by volume. At the combined spread rate of 387 ft^2/gal, dry thickness of the coating on the hardboard specimens would have been approximately 1.5 mils (0.0015 in., 0.0381 mm) (ITW Resin Technologies [no date]). By applying two thin coats of topcoat rather than one heavy coat, uniform and complete coverage was assured; the risk of depositing irregular globs or fillets of paint around specimen edges was avoided. The application of two thin coats, by virtually eliminating paint drips, also provided greater confidence in recorded paint application weights, but resulted in topcoat dry film thickness (1.5 mils) being considerably less than the industry-recommended value of approximately 3 mils, which would have been attained with two coats, each of approximately 1.5 mils dry film thickness, each applied at the paint manufacturer's recommended spread rate of around 400 ft^2/gal. All brush painting was performed in a conditioned laboratory. The drip edges and faces of specimens were painted, whereas specimen end cuts were left bare.

Test Building Exposure

Building and Exposure Characteristics

The test building, located at FPL's Valley View test site, was not conditioned (it was not heated or humidified in winter, nor was it air-conditioned in summer). The building was 48 ft (14.6 m) long and 8 ft (2.4 m) wide, with the long dimension in an east–west direction. Siding specimens were installed on the south wall of the building as lap siding courses in 28 columns of 10 boards per column. The exposure of each course was 6.625 in. (0.17 m) (as had been the case on the spray fences). The lowest course of siding was installed over a 3.375-in- (0.086-m-) wide strip of wood–plastic composite lumber that had been planed to 0.375-in. (9.52-mm) thickness (the same thickness as some commercial hardboard siding). The lowest siding course overlapped this strip by approximately 1 in. (25 mm). The means of mounting specimens on the building was essentially the same as that used to mount specimens on the spray fences, schematically depicted in figure 4 of Carll and TenWolde (2004); the wall framing was sheathed with 3/4-in. (19-mm) plywood, to which plywood nailing strips and treated lumber column separators were attached. The spaces between nailing strips and column separators were then filled with extruded polystyrene foam. The mounting means, which involved two layers of 3/4-in. (19-mm) plywood provided for ample embedment of siding nails. (Nailing strips were secured to the underlying layer of plywood with flat-head screws, with the heads flush with the surface of the nailing strip.) The foam between the nailing strips and column separators meant that the siding was not installed as a rainscreen; there was no continuous vertical air gap behind the siding because the top edge of each course of siding was in contact with foam infill or a plywood nailing strip. The building had been erected in the late 1970s; its existing length and the need to accommodate 28 columns of specimens limited specimen length to 17.75 in. (0.45 m). Each specimen was secured with two hot-dip galvanized nails, each placed 3/4 in. (19 mm) up from the drip edge. Given the exposure of each siding course, the nails penetrated the upper edge of the specimen one course below. The nails were laterally spaced at 12.5 in. (0.32 m).

Joints between the (unpainted) siding ends and the column separators were open (uncaulked), as had been the case on the spray fences. The gaps between specimen ends and column separators were roughly 0.25 in. (6 mm) wide. Open joints are contrary to industry installation instructions, as they allow water entry at board ends. Caulking the joints would have introduced a confounding variable. Caulked joints are subject to failure, particularly with lap siding, where depth of end joints inherently changes. Caulk joint failure is furthermore not predictable; in a study conducted in Florida (Carll and others 2000) some caulk joints allowed water entry while appearing intact. Had the joints been caulked, some of the joints would have failed, and failures would have occurred to varying degrees. The open joints in this study extended down past the bottom siding course, unlike an open joint or a failed caulk joint between siding and a window jamb casing. The extension of the open joints past the bottom siding course likely provided considerable drainage potential. The substantial width of open end gaps, coupled with the siding being true lap siding (as opposed to shiplap siding) and with the specimens being short, provided the opportunity for back face venting (from end to end of specimens).

Finally, the amount of water deposited as wind-driven rain into each open end joint was estimated as being roughly 15 L over the entire 155-month exposure period. The area of an open end joint was approximately 17 in^2 (0.011 m^2). A generous estimate of cumulative wind-driven rain intensity on the wall over the exposure period was 1,360 L/m^2 (see section in this paper concerning climatic conditions). This is a modest amount, particularly in contrast with water amounts that are potentially present at the heads or sills of fenestration units (windows and doors). The watershed area of a fenestration unit can exceed a couple square meters, and that of a building wall above a fenestration unit can be even larger. The amounts of water that would be deposited in these watershed areas during wind-driven rains could thus be substantial. Some significant portion of the wind-driven rain deposited in the watershed area above a window or door unit would be expected to run down the wall surface to the joint at the head of the unit. Likewise, some significant portion of the wind-driven rain deposited against a window would be expected to reach the horizontal joints at the sill of the window. The amounts potentially delivered to horizontal joints at window heads and sills by cascade wetting are dramatically higher than the estimated amount of water potentially deposited by wind-driven rain into tall narrow joints, such as the open end joints in this study.

In summary, the installation was expected to stress the (unpainted) ends of specimens and to result in some water entry behind the siding at specimen ends, but to allow each of these to occur in a largely consistent manner. Moreover, the amount of water deposited into the open end joints was calculated as being modest.

The test building had a shed roof that sloped to the south but had a 13-in. (0.33-m) overhang at the eave. The building's narrow north–south dimension resulted in a limited roof watershed area per unit length of eave. The roof was not guttered. Water from the eave fell on grass-covered soil, and the lower edge of the bottom course of siding was approximately 23 in. above ground level, resulting in limited potential for splash wetting. During a heavy rainstorm, with wind from the east, a wetted area that extended approximately 21 in. above ground level (about 2 in. below the drip edge of the lowest siding course) was observed. Because of the wind direction and puddling of water at the roof-edge drip-line, the wetted area was assumed to have resulted primarily from splash wetting. The observation was made in late winter, when the ground was saturated, and may have been partially frozen. The degree of puddling (a factor in splash wetting) was considerable, and was thus assumed to be greater than during most rainstorms. This observation largely confirmed that there was not great potential for splash wetting. The potential exposure of the building wall to wind-driven rain was influenced by wind direction during rainstorms, the building's surroundings, and its orientation relative to those surroundings. The building was located on a southwest-facing hillside, but there was another long single-story test building located 60 ft directly south of the building. The building was supported by posts; there was an open airspace below the building's wood-frame floor system.

Wall height (up to the soffit of the roof overhang) was 8 ft. The 10 courses of siding had a vertical combined exposure of 66.25 in. There were roughly 2 in. between the drip edge of the lowest siding course and the bottom of the 8-ft wall. There was thus approximately 28 in. of wall surface between the upper exposed surface of the top course of siding and the soffit of the roof overhang. This space was filled with an additional course of hardboard lap siding and, above that, plywood installed on the column separators (which served as furring strips for the plywood). During a rain event with a horizontal intensity of 0.2 in. per hour, with concurrent wind at 7 mph directly from the south, and assuming that the building provided no aerodynamic obstruction to wind, the uppermost course of siding would have been partially within a sheltered zone provided by the roof overhang.

These values for rainfall intensity (0.2 in h^{-1}) and wind speed (7 mph) were chosen on the basis of an analysis of data collected at the nearest National Oceanic and Atmospheric Administration (NOAA) weather station over the period of exposure. They were common values during wind-driven rains where horizontal rainfall intensity was substantially, but not dramatically, higher than average.
The assumption that the building provided no aerodynamic obstruction to wind is made solely for reasons of simplification and is known to be incorrect. Under this assumption, the sheltering effect of the overhang is minimized (actual sheltering will be greater than assumed).

Nails for securing siding specimens to the building were manually driven. A few mis-strikes occurred during installation (hammer glancing off nail head). None of the nails were noticeably overdriven. Cracking of the paint film at some nail heads was nonetheless observed in the fall of 1997 (shortly after installation) without the boards having undergone perceptible swelling. In late spring of 1998, the areas around all nail heads on the building, including areas where mis-strikes had occurred, were touch-painted with the same satin latex paint used to paint the specimens in the laboratory. Any paint cracking that occurred after the touch-up painting could thus have been attributed to behavior of the siding, rather than to installation issues. For the remainder of the exposure period (until removal in August 2010), no further paint cracking was observed at nail heads.

Specimen Placement

As indicated previously, three specimens for exterior exposure were obtained from each 8-ft strip of siding selected to provide test material. As cut, each of the three specimens was labeled to identify the strip from which it was cut and its position (left, middle, or right) in the strip. Assignment of left, middle, and right specimens to exposure (spray fence 1, spray fence 2, or building) was random, and varied from strip to strip. Twenty specimens of each of the 14 board classes (13 classes of hardboard siding and one OSB siding) were installed on the building (a total of 280 specimens). As indicated previously, the specimens were installed in 28 columns, 10 specimens in each column. Two specimens of each board class were assigned to each of the 10 courses, with column locations within each course assigned randomly. Assignment of two specimens from each siding class to each course compensated for potential variation in water exposure from course to course. As discussed in the Discussion and Analysis section of this paper, water exposure evidently was course-dependent.

Climatic Conditions—Rainfall and Decay Hazard Index

Specimens were installed on the building in September 1997 and were removed from the building in August 2010. Climatic conditions for each of the full years during the exposure period, at the nearest NOAA station to the Valley View site, are presented in Table 1. The weather station was located approximately 12 miles to the northeast at Dane County Regional Airport (weather station code KMSN). Precipitation is recorded in the data sets maintained by the National Climatic Data Center (NCDC) as water equivalent, whether the precipitation falls as rain, snow, or other varieties of freezing or frozen precipitation. Estimated rainfall was determined from monthly recorded values for precipitation and monthly recorded depth of combined fall of snow,

Table 1. Estimated rainfall and decay hazard index values at Madison for each of the full years during building exposure

Year	NOAA-recorded annual precipitation (in. (mm) water equivalent)	Estimated annual rainfall (in. (mm))	Decay hazard (Scheffer) index
1998	40 (1010)	36 (920)	47
1999	32 (810)	29 (730)	60
2000	40 (1020)	36 (900)	42
2001	38 (980)	37 (940)	57
2002	26 (670)	23 (580)	36
2003	32 (800)	29 (740)	40
2004	39 (1000)	37 (930)	53
2005	25 (630)	19 (480)	41
2006	37 (930)	33 (850)	47
2007	44 (1130)	38 (950)	43
2008	44 (1120)	34 (860)	40
2009	38 (970)	34 (850)	44
12-y summary	mean = 36 (920) COV = 18%	mean = 32 (810) COV = 19%	mean = 46 COV = 16%

ice pellets, and hail, using the calculation method used by Cornick and Lacasse (2009) for climate normal data. The rainfall and decay hazard index values varied considerably from year to year but were nonetheless moderate over the exposure period. During all years, decay hazard (Scheffer) index value was between 35 and 65, a range recognized as representing a moderate hazard for decay. The mean decay hazard index value was noticeably higher than calculated by Scheffer (1971) for Madison, and slightly above the index value calculated from climate normal data for the period 1971–2000 (Carll 2009). The higher mean Scheffer Index value over the 12 years (1998–2009) than for earlier periods concurs with increases in the Index value over recent decades in the coldest regions of the eastern United States (Lebow and Carll 2010) and in Canada (Morris and Wang 2008). For comparative purposes, rainfall and Scheffer index values for one location in each state east of the Mississippi and one location in each the states immediately west of the Mississippi over the period 1990–2009 are provided in the Appendix. A comparison of values in Table 1 with those in the Appendix indicates that average annual rainfall at the test site over the exposure period was lower than at most locations in the eastern half of the conterminous United States over the period 1990–2009. The exposure could thus be characterized as less challenging than average for the eastern states.

Climatic Conditions—Wind-Driven Rain

An estimate of cumulative wind-driven rain exposure on the south wall of the building over the period October 1, 1997, to August 15, 2010, was calculated from hourly data recorded at the KMSN weather station. Hourly values for wind-driven rain were calculated and the hourly values summed. Calculation of hourly wind-driven rain was by the equation in chapter 12 of Straube and Burnett (2005):

$$\mathrm{WDR} = \mathrm{RDF} \times \mathrm{DRF} \times V_{(1.75)} \times r_h \times \cos\Theta$$

where

WDR	is	wind-driven rain (L/m^{2}h)
RDF		rain deposition factor (dimensionless)
DRF		driving rain factor (s/m)
$V_{(1.75)}$		wind speed at 1.75-m height (m/s)
r_h		rainfall intensity (mm/h)
Θ		angle of wind relative to south (or an azimuth of 180°)

The calculation was thus for wind-driven rain intensity at 1.75-m height, which was substantially above average height of the test specimens on the building but below the height of the uppermost specimen in each column. RDF was set to a value of 0.8, which is substantially higher than average for walls in low-rise buildings. DRF is inversely related to terminal (vertical fall) velocity of raindrops and is thus inversely related to rainfall intensity. DFR was calculated using the following equation from Straube and Burnett:

$$\mathrm{DRF} = 0.22(r_h)^{-0.123}$$

Wind speed at 1.75 m was calculated as

$$V_{(1.75)} = \left(\frac{1.75}{10}\right)^{a} \times V_{(10)}$$

where $V_{(10)}$ is wind speed at 10 m (standard height at which wind records are collected) and $\alpha = 0.14$ (the value for open terrain, Straube and Burnett, chapter 3, 2005).

Hourly rainfall intensity values were obtained from hourly precipitation data by reference to weather observation codes in the NCDC data sets, using a simplified version of the adjustment method outlined by Cornick and Lacasse (2009)

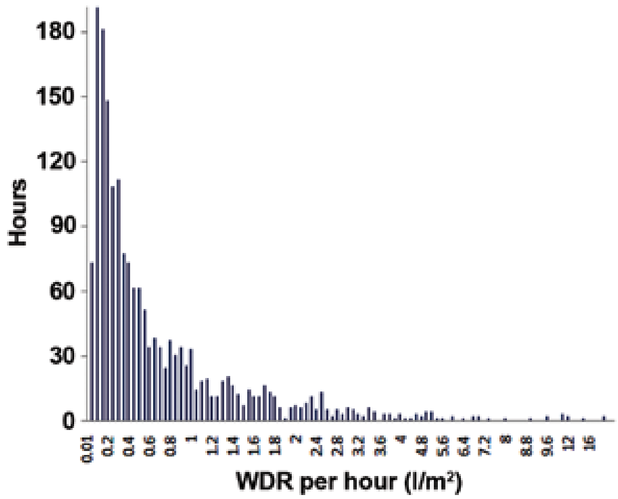

Figure 1. Hourly wind-driven rain (WDR) intensity values for weather station KMSN Madison, Wisconsin, for the period October 1, 1997, to August 15, 2010, against a south-facing wall at 1.75-m height.

for hourly data. Weather observation codes included in the hourly datasets were inputs for the adjustment method. The primary hourly weather observation codes that were pertinent were RA (rain), DZ (drizzle), and TS (thunderstorm). Eight other observation codes, which indicated various forms of freezing or frozen precipitation, were also relevant if they were present during the same hour as any of the three primary codes.

Cumulative calculated WDR was approximately 1,360 L/m^2 over the period October 1, 1997, through August 15, 2010. The cumulative wetting to which specimens on the spray fences had been exposed (from August 1997 through early October 2000) had been substantially greater. Wetting on the spray fences had two components: wind-driven rain exposure and spraying. Spraying had been by far the larger component. On spray fences, each of the 28 columns of siding had been wetted by a spray nozzle that delivered water at a rate of 15 mL/s. Spraying had occurred for 1 h each day during warm months. Each spray event had thus delivered 54 L of water to a column of siding. There had been approximately 580 spray events on each of the test fences, which amounted to a cumulative spray exposure per column of roughly 31,000 L. Surface area of the 10 siding courses on each column on the spray fences was approximately 0.96 m^2. Cumulative area-normalized spray exposure on the fences had thus been roughly 32,600 L/m^2. By comparison, calculated wind-driven rain exposure (at 1.75-m height) had been approximately 360 L/m^2 over the fence exposure period (approximately August 1, 1997, through October 12, 2000). Water exposure during spray fence exposure had thus clearly been dominated by spray wetting. Water exposure in spray fence exposure had been well in excess of 20 times the cumulative calculated WDR exposure on the building (32,960 L/m^2 versus 1,360 L/m^2) even though spray fence exposure was of shorter duration. Moreover, note that the calculated WDR values were generous estimates as they were calculated for 1.75-m height, and assumed a rain deposition factor of 0.8.

The data used to calculate WDR over the period October 1, 1997, through August 15, 2010, were further evaluated to identify the number of hours over the period during which there was wind-driven rain with some southerly component. A histogram showing the frequency (number of hours) of WDR at various levels of WDR intensity is presented as Figure 1. The figure shows that for most of the hours over the exposure period during which there was WDR, the WDR intensity was modest. The total number of hours during which there was wind-driven rain with a southerly component (total of all frequencies in the histogram) was approximately 1,800. By comparison, the total number of hours during which there had been wind-driven rain with some southerly component over the period August 1, 1997, through October 12, 2000, was 440. If these 440 h are assumed to have been in addition to the approximately 580 h of spray wetting, the total number of hours of wetting on the spray fences would have been 1,020. Therefore, the specimens on the building were evidently subjected to more hours of wetting than the specimens on the spray fences had been (1,800 h versus 1,020 h), in keeping with the longer exposure period, even though the amount of water to which they were exposed over the longer period was dramatically less.

Inspections

Inspection of specimens on the building were made in November 1998, October 1999, May 2000, October 2000, September 2002, September 2003, November 2004, September 2006, and September 2007. After removal of specimens from the building in August 2010, they were inspected inside a laboratory. Inspection was always made by the same individual. Each board was inspected for discoloration of the painted face and of the painted drip edge by mildew, for evidence of decay, for condition of the paint on the face and on the drip edge, and for edge welt. Welt is a term sometimes used in the hardboard siding industry to describe localized swelling along panel edges (Baldwin 1988). The swollen area projects beyond the normal panel surface plane, and the surface within the swollen area is irregular (that is, not flat). Some degree of fiber raising occurs in welted areas. Figure 2 shows edge welting as observed in two adjacent welt-prone specimens part way through the exposure period.

At the end of the exposure period, specimens were removed from the building by cutting a plug around each nail with a hole saw. This allowed removal of specimens without subjecting them to prying or gouging. During the final

Figure 2. Two adjacent specimens in a column, each showing edge welting. This photo was taken after roughly 7 years of exposure. Welting is predominantly at mid-length of specimen (between the nails). Note lack of perceptible swelling (or welting) at the nails. The points at which on-fence thickness was measured were slightly outboard of (toward specimens ends from) the nails.

inspection, severity and extent of edge welting at board ends was recorded. During field inspections, if edge welting had been present at board ends, its presence had been recorded, but no attempt had been made to quantify its severity or extent.

After the final inspection was complete, the extent of water stains on the back surfaces of boards was measured. Water stains were not a failure mode, but their extents and patterns can be instructive in helping explain how failure modes were likely to have begun. Measurement of the extent of water stains was performed in two phases. The first phase involved a set of measurements taken at the same locations where measurements had been made on specimens removed from spray fence exposure. Locations of these measurements were as shown in figure 14 of Carll and TenWolde (2004). This set of measurements included the distance by which staining extended upward from the drip edge at midspecimen length, and the distance by which staining extended inward from the ends of the specimen at four different locations, all of them above the lap area. Staining in the lap area at midspecimen length (Fig. 3) was only observed occasionally, with the extent of this staining varying considerably in the limited number of specimens where it was observed. In contrast, most specimens showed some staining extending inward from specimen ends above the lap area, although in some board classes, the extent of this staining was modest and its intensity faint (Fig. 4). Staining was of modest extent and faint intensity in classes 7, 11, and 13. Boards in classes 7 and 13 had back surfaces of dark color; this made perception of staining difficult, although identification of the stain extent generally was possible. Figures 3–5 are presented for illustrative purposes and thus do not

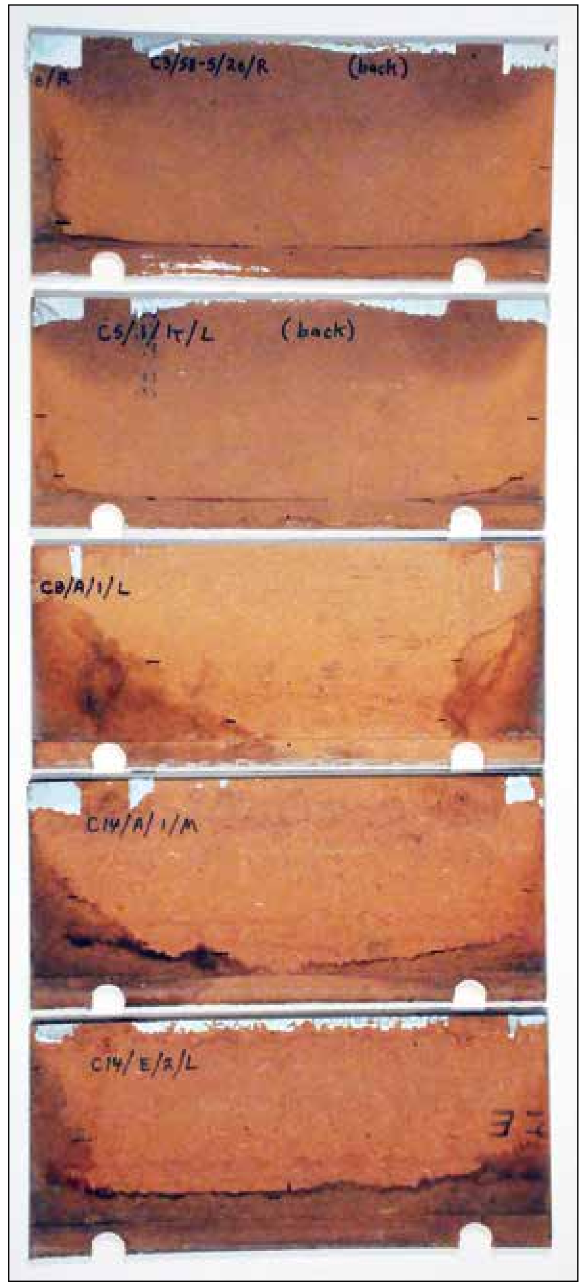

Figure 3. Rear surfaces of five specimens with staining at the drip edge at mid-specimen length. All five specimens also have staining above the lap area extending inward from the board ends, which is more extensive. The distance by which staining extends upward from the drip edge at mid-specimens length is modest in specimens C3/58-5/2e/R, C5/1/1$_T$/L, and C14/A/1/M. Intensity of staining at the drip edge is modest (faint) in specimens C3/58-5/2e/R and C5/1/1$_T$/L, but is perceptible. In all these specimens, staining at the drip edge is continuous between at least one end of the specimen and specimen mid-length.

Figure 4. Rear surfaces of five specimens with staining wholly or mostly restricted to areas above the lap. In specimen C11/A/3/L, the extent of staining is modest, and the intensity so modest as to be barely perceptible. With the exception of specimen C14/C/1/L, these specimens had more extensive staining than average for their respective board classes.

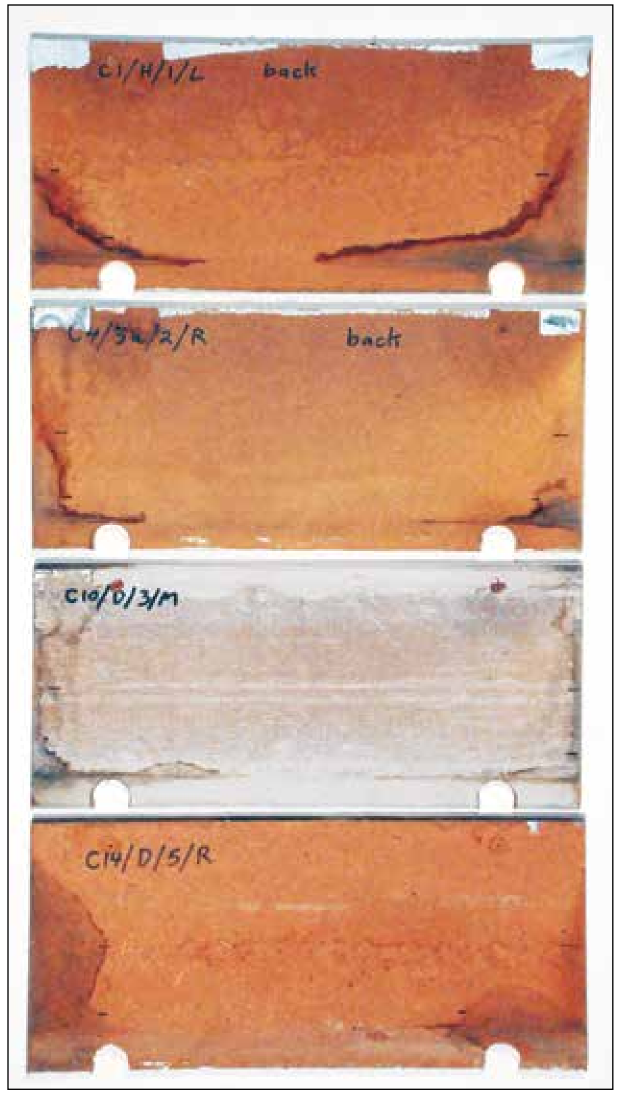

Figure 5. Rear surfaces of four specimens with staining above the lap area, extending to varying degrees into the lap area, and as far down as the drip edge on at least one specimen end, but not extending to specimen mid-length at the drip edge.

include specimens from board classes with dark-colored back surfaces.

Staining in the lap area that was restricted to board ends was also sometimes observed (Fig. 5). The second evaluation phase involved documentation of sideways extent of back-surface stains from board ends, in the lap area; measurements of stain extent were made at the drip edge.

Measurements made in the second evaluation, when compared with measurements made in the first phase, allowed a comparison of sideways extent of staining from board ends above the lap area with sideways extent of staining from board ends within the lap area.

Laboratory Tests

Moisture-Related Tests

As indicated previously, laboratory tests included weatherability of substrate, edge water absorption, and water vapor sorption. Description of the test procedures, and the test results, were previously reported (Carll and TenWolde 2004). Results of substrate weatherability testing are reiterated in Tables 2 and 3.

Table 2. Residual thickness swelling of noncommercial hardboards in substrate weatherability testing

Class	Average RTS[a] (%)	Standard deviation (%)	Specimens exceeding two RTS values (%) 20% RTS	17% RTS
1	5.9	1.8	0	0
2	6.7	1.3	0	0
3	8.9	2.0	0	0
4	12.0	2.5	0	9
5	22.7	3.2	80	99
6	30.1	5.6	99	99

[a]Average of 80 specimens.

Table 3. Residual thickness swelling of commercial hardboards in substrate weatherability testing

Class	Average RTS[a] (%)	Standard deviation (%)	Specimens exceeding (%) 20% RTS	17% RTS
7	11.5	1.2	0	0
8[b]	15.3	3.4	14	23
10	4.9	1.0	0	0
11	7.5	2.9	0	1
12	9.1	3.7	0	6
13	12.4	1.4	0	0
14	11.0	2.0	0	3

[a]Average of 80 specimens.
[b]Carll and TenWolde (2004) contains typographic errors in the average and standard deviation values for class 8 board in. The correct values are 15.3 and 3.4 (not 15.0 and 4.4).

At a criterion level of 17% RTS, differences between classes of commercial board were more apparent than at a criterion level of 20% RTS. At a criterion value of 20%, no specimens of class 7 or of classes 10–14 exceeded the criterion level. In contrast, at a criterion level of 17% at least one specimen in roughly half the classes of commercial board exceeded the criterion level. The proportion of test specimens in a class that exceeded a 17% RTS level was related to average RTS value for the class and variation in RTS value. The class 12 board showed the highest variation in RTS value. It had a higher proportion of specimens exceeding 17% RTS than did classes 7, 13, and 14, each of which had higher average RTS values. Class 12 boards had been mismanufactured; they contained press blows.[2] As will be discussed later, class 12 boards performed in a different manner on the building than boards of the other classes.

[2]Press blows are internal delaminations (voids) induced by internal steam pressure. They occur at press opening and are associated with higher than desirable mattress moisture content at press loading, a pressing cycle that does not adequately allow for steam dissipation, or a combination of these.

Significant proportions of specimens of class 8 board showed RTS in excess of either 20% or 17%.

Density Distribution Measurements

Density distribution through the board thickness was identified using a Quintek Measurement Systems QDP-01X Density Profiler (Knoxville, Tennessee) on specimens from all board classes except 9 and 12. Class 9 was excluded from density distribution evaluation on the grounds that it was OSB rather than hardboard. Class 12 was excluded on the grounds that, as stated previously, boards in this class contained press blows. The Profiler makes measurements on 2-in. (51-mm) square specimens. Six specimens of each class were evaluated. The specimens were cut from end portions of the (8-in. wide) strips that yielded outdoor exposure and laboratory test specimens; the specimens were cut from the inboard edges of the end portions. The material from which the specimens were cut had not been exposed to the weather, but instead had been maintained in long-term storage under controlled temperature and humidity.

Density was calculated by the instrument, based on attenuation of a collimated X-ray beam passing, in series, through the test specimen and a slit measuring approximately 0.002 in. (0.05 mm) by 1.0 in. (25.4 mm). In the instrument, specimens are presented to the X-ray beam by a specimen holder. Position through the specimen thickness is determined by position of the specimen holder, which is in turn controlled by a stepper motor and its controller system. Scan values at steps near the board faces are potentially influenced by the X-ray beam passing in part through air adjacent to the specimen, and in part through the surface layer of the specimen. This is discussed in the user guide provided by the instrument manufacturer, largely in the context of "misaligned" specimens (specimens whose surfaces are not parallel). The specimens (which had limited length and width dimensions and which had been stored under controlled conditions) showed no perceptible taper or cup, and the effect of "misalignment" was thus not considered as being significant. Density readings taken at less than 0.004 in. from either specimen face were, however, ignored. Specimens of commercial board were stripped of primer paint.

A first set of measurements had been made on specimens of commercial board as cut (with primer paint). It became evident from this set of measurements that the primer had a higher X-ray attenuation coefficient than the hardboard substrate, and that this interfered with obtaining accurate density distribution measurements in the substrate. Stripping of primer was performed in a series of steps with "no-wash" (volatile) liquid stripper, a freshly sharpened paint scraper, and 320-grit abrasive paper.

A summary of the density distribution measurements is presented in Table 4. Each "scan" in this process represented a prism of width equal to the slit (0.002 in.) For purposes of presentation, the individual density scans for a specimen

Table 4. Summarized layer density measurements obtained by X-ray densitometry

Board class	Average density in face-layer zone (kg/m^3)	Density ratios		Layer zone containing highest density scan for specimen	Density ratio highest density scan to layer zone density
		Face : core layer zones	Face : back layer zones		
1	726	0.86	0.92	variable	
2	824	1.04	1.00	back	1.12
3	849	1.10	0.98	back	1.18
4	815	1.10	1.01	back	1.21
5	853	1.00	1.06	variable	
6	849	1.07	1.06	variable	
7 (com)	869	1.16	1.22	face	1.10
8 (com)	970	1.16	1.06	face	1.06
10 (com)	1009	1.09	1.08	face	1.10
11 (com)	907	0.98	1.01	variable	
13 (com)	785	1.07	1.01	face	1.08
14 (com)	809	1.10	1.11	face	1.08

(each for a prism as wide as the slit) were segregated into three “zones”: a face-layer zone (incorporating the outer quarter thickness of the specimen), a core-layer zone (incorporating all layers between quarter-thickness points), and a back-layer zone (incorporating the back quarter thickness of the specimen). The third column of Table 4 indicates that, with the exception of board classes 1, 5, and 11, average density in the face-layer zone exceeded that in the core-layer zone. For board class 1, average density within the face-layer zone was less than that in either core-layer or back-layer zones, while for classes 5 and 11 average densities in the face-layer and core-layer zones were essentially equal. The fourth column of Table 4 indicates that for commercial boards, with the exception of class 11, density in the face-layer zone exceeded that in the back-layer zone (column 4). The fifth column indicates that for commercial boards, again with the exception of class 11, the location of the highest individual density reading (scan) was in the face-layer zone. For noncommercial boards, density in the face-layer and back-layer zones tended to be more similar (column 4), and the zone in which the highest density scan was located, while more commonly in the back-layer zone than elsewhere, was somewhat variable (column 5). Values in column 6 of Table 4 indicate (where appropriate) within-zone variability in density. Values are listed in column 6 for those board classes where the location of the highest density scan was consistently in one zone. The values indicate considerable, but not extreme, density gradients within zone layers.

Class 10 boards had higher density in the face-layer zone than any other class (column 2), and consistently had higher density in the face-layer zone than in core-layer or back-layer zones (columns 3 and 4). On a proportional basis, uniformity of density in the face-layer zone was similar in class 10 boards to that in other classes of commercial board (Table 4, column 6). In absolute terms, however, class 10 boards had more density variation within the face-layer zone than other board classes. In boards of class 10, the highest density scan (which was within the face-layer zone) was consistently within 0.2 mm of the surface, whereas in some classes of commercial board (classes 7 and 14) the highest density scan was typically 1 mm or more from the board’s outer surface.

For one specimen of each of commercial board classes 8, 10, and 14, an imprecise gravimetric check of density distribution was also made. A stationary wide-belt sander was used to remove successive 0.003-in. (0.076-mm) passes from the surfaces of 8-ft strips of board. (The board strips were spares that had been stored under controlled conditions. In one case, thickness variation along the strip length precluded making measurements on the full length strip. In this case, the strip was crosscut into two 4-ft strips). The specimens were weighed between each successive pass. The gravimetric measurements were imprecise because of thickness variation, which was considerable in the (relatively) wide and long strips. The gravimetric measurements confirmed, however, that the densities of surface layers of these boards were higher than their respective average board densities.

Results

Two failure modes became evident over the exposure period, namely cracking of paint on drip edges and edge welting. With the exception of very limited mildew growth, other failure modes were not observed. In-service thickness, and the extent of back-surface water staining (measured after specimens were removed from the building) are also reported in this section of the paper. These moisture-related behaviors do not, of themselves, necessarily result in problems, although they may in some cases relate to the problematic behaviors (“failure modes”) observed.

In-Service Thickness

As can be seen in Figure 6, siding thickness, measured at the drip edge, did not progressively increase over the first

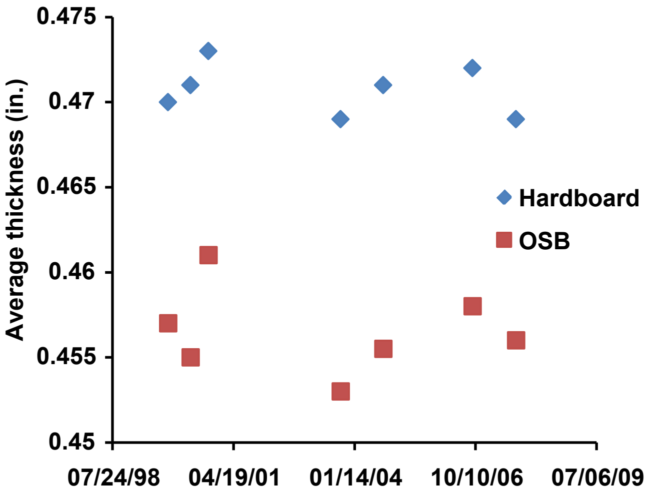

Figure 6. Siding thickness, measured in-place at the drip edge, on seven dates between October 1999 and September 2007. Neither the hardboard sidings nor the OSB siding underwent progressive thickness swelling, despite nearness of open end joints to the points at which thickness was measured.

decade of exposure. Localized edge swelling often became visually apparent at the specimen ends. The swelling at specimen ends, being localized, did not affect measurements made at the drip edge roughly 2 in. (51 mm) from the specimen ends. As mentioned previously, after paint touch-ups in July 1998, cracking of paint at nail heads did not occur during the exposure period. At specimen removal in August 2010, there was no observable paint cracking or thickness swelling at nail heads. Cumulative wetting of the boards over the exposure period was not sufficient to cause measurable swelling near the nail heads (where thickness was measured). Figure 2 shows that swelling at the drip edge sometimes occurred. It did not, however, occur at the points where thickness was measured. On the spray fences, the same spatial pattern of drip edge swelling had occurred (least near the thickness measurement points) but measureable and progressive swelling had nonetheless been recorded (figure 10 of Carll and TenWolde 2004). The lack of measureable thickness swelling of specimens on the building (as opposed to measureable thickness swelling on the fences) is most likely attributable to less water exposure on the building than on the fences.

Staining of Back Surfaces

Measurements taken during the first evaluation phase are summarized in Table 5. As indicated previously, these included (a) lateral extent of stain from board ends, with measurements taken above the lap area, and (b) upward extent of stain from the drip edge, measured at midspecimen length. For purposes of comparison, mean lateral extent of stain from board ends as measured at the end of exposure on spray fences are included in the two rightmost columns of Table 5.

The average extent of back-surface staining in the area above the lap was, in most cases, less than had been observed on spray fences, although there were a few exceptions. Boards in classes 1, 2, and 13 on average showed slightly more staining above the lap area after 155 months of exposure on the house than they had after 39 months of exposure on the spray fences, while OSB siding showed similar extents of above-lap staining in the two exposures. Boards in all the other classes showed lesser extents of above-lap staining than they had in spray fence exposure; classes 8 and 14 showed dramatically less above-lap staining than they had in spray fence exposure. Similarity of mean and median values for lateral extension of stains from board ends in areas above the lap (Table 5) indicate that the data distributions for this parameter are not significantly skewed. A difference between the exposures (spray fences versus building) was more apparent in the degree of staining within the lap area. Whereas roughly 40% of the hardboard specimens removed from the spray fences had shown some staining extending upward from the drip edge at mid-length of the specimen, roughly 7% of the hardboard specimens (only 18 of the 260) removed from the test building showed such staining.

Measurements taken during the second evaluation phase are summarized in Table 6. Median values for lateral extent of staining from board ends were much lower at the drip edge than they were above the lap area (compare median values in Tables 5 and 6). The same was generally true, although to a less dramatic degree, for mean values. With the exception of the 18 specimens where staining at the drip edge was present at mid-specimen length, the lateral extent of staining from board ends at the drip edge was modest. Median values in Table 6 are, without exception, lower than mean values, indicating skewed data distributions. The median values also indicate that the majority of specimens showed no inward extent of staining from board ends at the drip edge.

Board classes 8 and 14 generally showed the most extensive back face staining, although there were as many (or more) specimens of board class 5 and class 6 with staining at the drip edge at mid-specimen length as there were for any other class (Table 5). Also, the mean inward extent of staining within the lap area was higher for classes 5 and 6 than for any of the other classes (Table 6). The maximum extent of staining above the lap area (observed in any one specimen) was highest for two specimens of class 8 board, and next highest for a specimen of class 14 board. Above the lap area, mean and median values for inward extent of staining from board ends were also higher for classes 8 and 14 than for classes 5 or 6. In spray fence exposure, board classes 8 and 14 had likewise shown more extensive inward staining (above the lap area) than any of the other board classes. Board classes 5, 6, 8, and 14 had shown the highest values of edge water absorption in laboratory testing (Carll and TenWolde 2004), with class 14 showing by far the most

Table 5. Parameters relating to water staining on backs of siding boards (evaluation phase 1)

	Inward staining from ends (measured above the lap area) (in.)			Upward staining from drip edge (at mid-specimen length)		Mean inward staining (measured above the lap) in fence exposure (in.)[a]	
Class	Mean	Median[b]	Max.[b]	Number specimens showing stain	Maximum upward extent (in.)	Fence 1 drip edges not painted	Fence 2 drip edges painted
1	1.84	1.63	3.56	0		0.93	0.92
2	0.85	0.84	1.31	0[c]		0.45	0.46
3	1.24	0.98	5.25	1	0.125	1.31	1.26
4	1.07	0.83	3.88	0[c]		1.03	1.14
5	1.06	0.98	1.81	5[c]	0.375	1.78	1.96
6	1.03	1.05	2.41	4[c]	0.25	1.47	1.87
7	0.46	0.50	0.71	0[c]		0.90	0.90
8	4.74	4.44	8.88	4	4.00	10.76	9.57
10	0.80	0.77	1.22	0		1.90	1.69
11	0.25	0.25	0.47	0		0.41	0.70
12	1.56	1.56	2.06	1	0.75	2.41	2.68
13	0.98	0.92	1.91	1[d]	0.375	0.78	0.70
14	1.96	1.55	6.50	2	2.00	8.20	8.12
OSB	0.55	0.53	1.09	0		0.45	0.40

[a]From table 5 of Carll and TenWolde (2004).
[b]Median and maximum values are for specimen average values rather than for individual measurements (four measurements per specimen).
[c]One specimen (not counted) with faint tinting close to the drip edge that could not be conclusively identified as water staining.
[d]Three specimens (not counted) with faint tinting close to the drip edge that could not be conclusively identified as water staining.

Table 6. Summary of staining extent laterally from specimen ends, at specimen drip edges

Board class	Inward extent of back-surface stain at drip edge (in.)		
	Mean	Median	Maximum[a]
1	0.39	0	6
2	0	0	0
3	0.38	0	10.38
4	0.23	0	1.75
5	2.32	0	8.88
6	2.66	0	8.88
7	0.01	0	0.25
8	1.61	0.13	12
10	0.03	0	0.5
11	0	0	0
12	0.66	0	4.5
13	1.00	0	10.5
14	1.30	0	11.38

[a]Maximum extent for any single stain. If staining is not continuous along the entire specimen length, and is predominantly from one end of the specimen, the extent can exceed half of specimen length.

water absorption. All of these board classes had shown higher than average levels of RTS in laboratory testing, although class 14 had shown significantly less RTS than classes 5, 6, or 8 (Tables 2 and 3).

In summary, back-surface staining of specimens removed from the house was, with few exceptions, considerably less than had been observed on specimens removed from the spray fences. The generally more prevalent and extensive back-surface staining on boards that had been exposed on spray fences was in concurrence with the relatively high cumulative area-normalized water exposure values on the fences, which as stated previously had been over 20 times as great as on the building. The relative amounts of staining between different board classes were, for the most part, similar to what had been observed on the spray fences.

As indicated previously, only 18 of the specimens (slightly less than 7%) showed staining upward from the drip edge at specimen mid-length. In all except one of the 18 specimens, the water stained area was continuous with at least one end of the specimen, indicating that the water could have entered from specimen end(s), rather than by capillary rise in the lap. The single specimen where the stained area at mid-specimen length did not appear to connect with specimen ends was a board of class 8. There was, with the exception of this specimen, lack of evidence of capillary water rise at hardboard siding laps. In addition, the extent of water-staining in lap areas was typically much less than in areas just above the lap (Figures 3–5 and Tables 5 and 6). Water that entered at specimen ends and was thus present at the upper edge of the lap near the board ends, was not pulled into the lap by capillary suction. The few exceptions were a limited number of specimens of classes 5, 6, 8 and 14. The typical lack of evidence for capillary wetting concurs with what had previously been observed on specimens removed from the

Table 7. Extension of drip-edge paint cracking from unpainted specimen ends

Board class	Extent of drip-edge cracks from swollen specimen ends (mm)		
	Mean	Median	Maximum
1	6	5	13
2	6	5	14
3	10	9	40
4	11	10	42
5	20	16	75
6	26	22	55
7	6	5	9
8	Continuous[a]		
10	8	8	10
11	6	5	14
12	Continuous[a]		
13	6	5	15
14	11	10	43

[a]Drip-edge cracks at specimens ends typically (class 8) or always (class 12) connected with patches of drip edge cracks that extended along most of, or the entire, specimen length.

spray fences (Carll and TenWolde 2004), with investigations performed by Tsongas and others (1998, 2004), and with observations of back surfaces of hardboard lap siding removed from test buildings in Florida (Carll and others 2000).

Paint Performance

The satin paint did not perceptibly lose its sheen, nor did it chalk or erode to any obviously noticeable degree. Film thickness of the satin topcoat paint at the end of the exposure was measured using ImageJ software (National Institutes of Health [no date]) on micrographs. Film thickness was, on average 29 µm (1.2 mils) on board surfaces, and 32 µm (1.3 mils) on drip edges, indicating that modest erosion of the paint film had occurred. With the exception of what occurred on drip edges, the paint did not crack, nor did it peel or flake. As discussed in detail under a separate heading, edge welting developed in somewhat over half of the hardboard specimens by the end of the exposure period. Paint remained adhered to welted areas on board faces, although rupture of the paint film adjacent to the welted area (at the intersection of the outer face and the drip edge) was common. Stated another way, paint performance on board faces was excellent, but paint cracking on drip edges was common, and was the most prevalent failure mode observed over the exposure period. Some degree of drip-edge paint cracking occurred in over half of the specimens of all board classes, except class 1, by the end of the exposure period. In class 12 boards, edge paint cracking commonly progressed to the degree that the paint flaked off the drip edge.

Localized drip-edge paint failures commonly occurred early during the exposure period at the ends of specimens where the drip edge intersected with the specimen end cuts. As indicated previously, the specimen end cuts were not painted and localized edge swelling occurred at end cuts. Where the end cut intersected the drip edge, the localized swelling resulted in rupture of the paint film (at the ends of the drip edge). The rate at which drip-edge paint cracks extended from the specimen ends progressed slowly. At the final inspection, at roughly 75% of specimen ends, extension of drip edge cracks from swollen ends did not exceed 15 mm. In specimens that developed prominent drip-edge paint cracking, the cracks typically developed in patches along the drip edge, often at some distance from the board ends. Until cracking progressed to advanced stages, the patches did not connect with cracks at the specimen ends. A summary of the extent to which drip-edge paint cracks extended from the swollen ends of boards at the final inspection is shown in Table 7. The linear extents were typically modest and thus most convenient to measure on a millimeter scale. In boards of classes 8 and 12, drip-edge cracking was typically continuous along the entire length of the drip edge at the final inspection. In all other classes of board, patches of drip-edge cracks, which were typically most prevalent near specimen mid-length, rarely or never connected with board ends at the final inspection.

During each of the in-field inspections, drip-edge paint cracks that were restricted to board ends were ignored. Table 8 summarizes observations made with regard drip-edge paint cracking over the exposure period (observations that disregarded cracking if it was restricted to board ends). The table indicates a general increase in the prevalence of drip-edge paint cracking as the exposure period progressed. In the overwhelming majority of cases, the number of specimens with cracks became progressively larger as the exposure period progressed. There are a few cases where the recorded number of specimens with drip-edge cracks decreased between successive inspections. These cases reflected observation of a minor paint crack at an inspection, followed by failure to detect the crack at the next inspection. All except one specimen of class 12 board showed readily observable drip-edge paint cracking after 14 months of exposure (in November 1998), whereas in all other hardboard classes only two or fewer specimens showed drip-edge paint cracks at that time, which were typically minor and generally not detected at the next inspection. As indicated previously, boards of class 12 contained press blows. Drip-edge paint cracks developed at the press blows.

The prevalence and severity of drip-edge paint cracking after 155 months of exposure on the building generally corresponded with what was observed on one of the spray fences after 39 months exposure. Specimens on one of the spray fences had been installed with drip edges intact (not cut off). Values for prevalence and severity of drip-edge paint cracking on that fence at the end of exposure (39 months) are presented in Table 9. They are generally similar to the values in the right two columns of Table 8, although there are some moderate differences. Drip-edge paint cracking in noncommercial boards tended to be roughly as prevalent, but more severe in accelerated (spray fence) exposure

Table 8. Prevalence of drip-edge paint cracking over exposure time, and average severity of drip-edge cracking at final inspection

Board class	Number of specimens with drip edge paint cracks at various inspection dates[a] 11/1998	11/1999	5/2000	10/2000	9/2002	9/2003	11/2004	9/2006	9/2007	after 8/10	Average severity after 8/2010
1	0	0	1	0	1	0	0	1	3	2	very minor
2	0	0	1	0	0	1	2	1	16	16	minor
3	0	1	0	1	0	5	5	3	16	17	minor
4	0	0	0	1	0	1	1	5	17	19	minor
5	2	0	1	1	3	1	2	3	8	13	minor
6	2	0	0	1	3	5	6	6	17	17	moderate
7	1	0	0	0	2	7	4	7	18	20	moderate
8	0	0	7	16	20	20	20	20	20	20	severe
10	0	0	1	6	8	18	18	19	19	20	significant
11	1	1	1	3	2	5	5	4	11	11	minor
12	19	20	20	20	20	20	20	20	20	20	severe
13	1	0	0	1	1	4	0	0	7	11	minor
14	0	0	1	4	5	10	14	15	18	19	moderate
OSB	4	1	1	3	6	12	11	11	17	18	moderate

[a]Specimens with drip-edge cracks only at specimen ends were not included in the count numbers.

Table 9. Prevalence and severity of drip-edge paint cracking at termination of spray fence exposure[a]

Board class	Number of specimens with drip-edge cracking	Average cracking severity
1	11	minor
2	5	minor
3	18	moderate
4	15	moderate
5	17	significant
6	19	significant
7	5	minor
8	16	significant
10	18	significant
11	10	minor
12	20	significant
13	14	minor
14	16	moderate
OSB	18	significant

[a]Inspection terminated October 2000.

than in long-term exposure. This is probably because of the higher cumulative wetting of specimens on the spray fences, and that specimens in long-term exposure on the building, unlike specimens on the spray fences, had not undergone measurable thickness swelling. In contrast, drip-edge paint cracking in board classes 7 and 8 tended to be less prevalent and severe in accelerated exposure than in long-term exposure. This suggests that development of drip-edge paint cracking is to some degree time-dependent as well as dependent on the degree of in-service wetting, and that the relative influence of these two factors can vary between boards from different production plants. Time-dependent development of drip-edge cracks may be related to change in properties of the paint films over time.

Location of the most prominent drip-edge paint cracking, relative to the front or back of specimens, was identified for each specimen at the final inspection. A summary of the observations is presented in Table 10. The count values in this table, when taken by board class, summed across the columns do not always exactly match the count values in the column in Table 8 for August 2010. There thus were minor inconsistencies in the observations; the origin of the inconsistencies invariably involved small cracks that were not visible without a hand lens. Regardless of the minor inconsistencies, the values in Table 10 convincingly indicate that paint cracking on drip edges was more prevalent near the outer face of the specimen than near the back of the drip edge. Relatively rare were the cases where drip-edge cracking was as prevalent or more prevalent near the back of the drip edge as near the front of the drip edge. In these cases, water stains on the back surface of the board at the drip edge were present, and the stains were near the drip-edge cracks. These cases were in specimens of classes 5, 6, and 14. Water intrusion into lap areas was thus evidently occasionally associated with development of drip-edge paint cracking. In the majority of cases, however, development of drip-edge paint cracks was apparently associated with something other than water intrusion into laps.

Edge Welting

Edge welt was characterized by a visually estimated severity rating and an associated index rating. The severity rating was influenced by the degree to which the welt projected beyond the board plane, the abruptness with which it projected, and the surface roughness within the welted area. A rating of 10 indicated no perceptible welt. A rating of 9.5 corresponded with welt that could be perceived when the surface was viewed obliquely, while a rating of 9 corresponded with welt perceptible when the surface was viewed

Table 10. Location of drip edge paint cracks relative to specimen faces or backs.

Board class	Prevalence of drip-edge paint cracking (no. of specimens) Most prevalent near the outer face	Equally prevalent near specimen back as near face	Most prevalent near the specimen back
1	1	0	1
2	16	0	0
3	16	1	0
4	19	1	0
5	7	3	7
6	10	4	2
7	19	0	0
8	19	0	0
10	20	0	0
11	11	0	0
12	20	0	0
13	10	0	1
14	16	1	2

Observations made at final inspection.

from a position normal to the board surface. Ratings lower than 9 indicated progressively more noticeable welt. As had been the case for specimens exposed on spray fences, an index value for edge welting was calculated for each specimen. The area of perceptible welt was combined with the severity rating into an index value as follows:

$$\text{Index} = \text{Area} \times (10 - \text{severity})$$

where area was in units of in^2.

Edge welting on the specimen surface at the drip edge, typically near mid-length, developed to various degrees in all classes of hardboard siding, although very little welting was observed in boards of classes 1, 2, and 11. No perceptible edge welting occurred in any of the OSB siding specimens over the course of exposure. The textured surface of the OSB siding apparently obscured edge welting. Values presented in Table 11 indicate the degree to which edge welt developed in specimens as the exposure period progressed. In most cases, the number of specimens with perceptible edge welting progressively increased as the exposure period progressed. As was the case for development of drip-edge cracks, cases occurred where there were reversals in recorded number of specimens with perceptible welt between inspections. These invariably involved the perception of a welt on a specimen with a severity rating of 9.5 (visible only obliquely) at an inspection, followed by failure to perceive welting in the specimen at a subsequent inspection or at subsequent inspections. Light conditions influenced the degree to which a welt was perceptible. Although care was exercised to limit the degree to which light conditions varied during inspections, some variation inevitably occurred. At some inspections, moveable shading was used to control light conditions. This is described in greater detail on page 13 of Carll and TenWolde (2004). Recorded values were thus not always consistent, especially when welting was near the threshold of perceptibility. Inconsistency in the recorded prevalence of edge welting is most noticeable for class 13 boards, no specimens of which showed a welt severity rating worse than 9.5 until September 2006; class 13 boards furthermore showed a low average value for welt index at the end of exposure. Despite imperfect consistency in the values found in Table 11, the values indicate an overall trend for edge welting to become progressively more prevalent with increased exposure time. A comparison of values in Tables 8 and 11 indicate that drip-edge paint cracking commonly preceded development of welt.

The values in Table 11 for average welt index are reported to three or four significant digits to show that the averages for classes 1, 2, and 11 were not zero. The values are, with only one exception, lower than previously reported (Carll and TenWolde 2004) for specimens exposed in accelerated exterior exposure (on spray fences) at the end of their

Table 11. Prevalence of drip-edge welting over exposure time, and average welt index rating at final inspection

Board class	Number of specimens with perceptible edge welt At 11/98	At 11/99	At 5/00	At 10/00	At 9/02	At 9/03	At 11/04	At 9/06	At 9/07	After 8/10	Average welt index values after 8/10
1	0	0	0	1	0	0	0	3	2	1	0.001
2	0	0	0	0	0	0	0	1	7	4	0.03
3	0	0	0	0	0	0	1	8	11	13	0.50
4	0	0	0	1	0	0	1	12	15	15	0.62
5	0	0	0	2	2	1	3	4	10	9	0.44
6	0	1	1	4	3	1	1	9	15	15	1.06
7	0	0	0	0	1	0	3	9	16	19	0.88
8	0	0	5	9	19	18	20	20	20	20	7.72
10	0	0	0	0	0	2	4	14	17	19	0.50
11	0	0	0	0	0	0	0	2	3	2	0.03
12	0	0	0	0	0	0	0	10	15	17	0.97
13	0	0	0	7	2	1	2	7	11	5	0.09
14	0	0	0	0	0	0	0	7	8	9	0.16
OSB	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Table 12. Descriptors for welting at board ends and selected descriptors for welting at drip edges

	Edge welting at board ends						Edge welting at drip edge			
	Number of ends with welt	Sideways extent from end (in.)		Welt severity rating		Mean index rating	Upward extent from drip edge (in.)		Welt severity rating	
Board class		Mean	Most[a]	Mean	Worst[b]		Mean	Most[c]	Mean	Worst[d]
1	11	0.07	0.13	9.9	9	0.02	0.06	0.06	9.95	9
2	23	0.09	0.13	9.7	9	0.09	0.19	0.50	9.9	9
3	40	0.13	0.19	8.9	8	0.88	0.21	1.0	9.4	9
4	40	0.13	0.25	9.0	8	0.87	0.17	0.38	9.3	9
5	40	0.16	0.25	8.8	8	1.19	0.20	0.63	9.6	8
6	40	0.17	0.38	8.7	8	1.33	0.20	0.38	9.3	8
7	39	0.12	0.25	9.1	8	0.67	0.15	0.38	9.1	8.5
8	40	0.29	0.50	8.6	7.5	2.73	0.83	1.38	9.1	8.5
10	36	0.07	0.13	9.2	8.5	0.28	0.08	0.13	9.1	8.5
11	15	0.07	0.13	9.7	9	0.06	0.09	0.13	9.9	9
12	32	0.10	0.13	9.5	9	0.23	0.21	0.25	9.4	9
13	37	0.10	0.25	9.2	8	0.54	0.10	0.13	9.8	9
14	19	0.11	0.25	9.7	8.5	0.18	0.21	0.50	9.6	9

[a] Greatest extent measured on any of 20 specimens (40 ends).
[b] Lowest (worst) rating observed on any of 20 specimens (40 ends).
[c] Greatest extent measured on any of 20 specimens (20 drip edges).
[b] Lowest (worst) rating observed on any of 20 specimens (20 drip edges).

exposure period. Without exception, the values are dramatically lower than those for specimens that had been exposed on a spray fence with their painted drip edges removed. Average class index values for spray fence specimens with painted drip edges removed ranged from 6.6 times higher to multiple orders of magnitude higher than the corresponding average class index values of specimens after building exposure (table 9 of Carll and TenWolde 2004). With one exception, the values are also lower than for specimens that had been exposed on a spray fence with their painted drip edges not removed (again, see table 9 of Carll and TenWolde 2004). The exception was class 10 board. Average welt severity and index values for class 10 boards at the end of fence exposure had been 9.7 and 0.2 respectively, better than the corresponding values (9.0 and 0.5) at the end of building exposure. Class 10 boards on the building showed prevalent drip-edge paint cracking in September 2003, less than halfway through the 155-month exposure period. Welting evidently originated at the drip-edge cracks, becoming progressively worse from September 2003 onward. Edge welting in class 10 boards never extended far above the drip edge, but was nonetheless readily perceptible; it consistently had a severity rating of 9 at the end of building exposure.

Table 11 indicates substantial differences in welt performance between classes of boards. Board class 1 showed the best performance, followed by classes 11 and 2. Board class 8 showed by far the worst welting. Board classes 5, 6, and 14, which had shown poor (high) welt index values in fence exposure, showed reasonably good (low) welt index values in building exposure. These boards, however, showed prevalent drip-edge paint cracking at the end of exposure. Inasmuch as drip-edge paint cracking typically preceded the development of edge welting, it is reasonable to expect that welting near the drip edges of boards in classes 5, 6, and 14 would have become progressively worse had their exposure continued.

Edge Welting at Specimen Ends

As indicated previously, localized swelling occurred at board ends. This often gave the ends a "broomed" appearance, which was most noticeable where board ends intersected with drip edges. Welted areas tended to eventually develop near the swollen ends, although welting at board ends was not noted prior to September 2006. As indicated previously, quantification of welting at board ends was not attempted until after the boards were removed from exposure. The orientation in which specimens were held during inspection influenced the degree to which welting at board ends was perceptible. During evaluation of board ends for welting, the specimens were thus rotated so that board ends were in the same orientation relative to the inspector as drip edges had been when the boards were evaluated for welting at the drip edge. Perceptible welting at board ends did not occur in OSB siding, even though localized swelling at ends of these boards was observable. Table 12 provides descriptors for welting at board ends, and for comparison, descriptors for welting at board drip edges.

Table 12 indicates that the upward extent of welting from drip edges generally exceeded sideways extent of welting from board ends, although for all board classes except class 8 it was always less than the lap dimension. For class 8 boards, the upward extent (distance) of welting from drip edges was roughly three times greater than the sideways extent of welting from board ends. For all other board classes, differences between upward extent of welting from drip

Figure 7a. Magnified image of the end of the drip edge of a specimen of Class 1 board. Drip-edge paint cracking is prevalent near the end of the specimen, but does not extend more than 16 mm from the specimen end. Patches of mildew are present only near the inboard terminations of drip-edge cracks. This specimen was from a bottom course location, (where water exposure was greatest), and in the left-most column of specimens (at the southwest corner of the building). This specimen showed more drip-edge mildew than any other specimen. In this photograph the outer specimen face is at the top of the specimen.

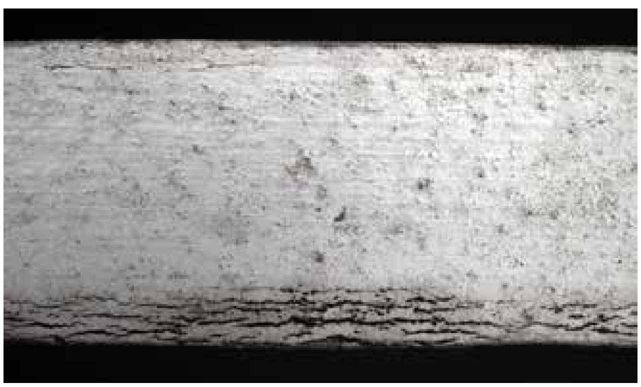

Figure 7b. Magnified image of the drip edge of a specimen of class 4 board approximately at specimen mid-length. A patch of drip-edge cracks is present near the outer edge of the drip edge, and a small amount of mildew is present in the patch of drip-edge cracks. The specimen was from a bottom course location. In this photograph, the outer specimen face is at the bottom of the specimen.

edges and sideways extent of welting from board ends were relatively minor, although upward extent of welting from drip edges nonetheless typically exceeded sideways extent from ends. In contrast to extent of welting, welt severity ratings tended to either be similar at board ends as at drip edges, or slightly higher at board ends. Regardless of the parameter chosen to express it (whether prevalence, measured extent, severity rating, or index value), welting at board ends was consistently worst in boards of class 8.

Decay and Mildew

There was no outward (macroscopically visible) indication of decay in any of the specimens. Mildew growth on painted surfaces was rarely noted, and where noted was confined to small patches, always close to the drip edge, usually in a welted area, or near drip-edge paint cracks, or both. Mildew growth had not been noted during any of the in-field inspections. At the final inspection, (performed in a humidity controlled laboratory) only seven specimens showed mildew patches. Mildew patches on these specimens were, as stated previously, small; the largest two mildew patches had an area of roughly 2.5 in^2 (1.6×10^{-3} m^2). Three of the seven boards with mildew patches, and the boards with the largest mildew patches, were boards of class 6. Limited patches of mildew, typically growing through the paint film, were present on the drip edges of a few specimens, always near drip-edge cracks (Figures 7a, b). These patches were easily visible with a 10 power hand lens, but were not readily perceptible without magnification.

The building wall, as indicated previously, faced south and was not shaded, so had ample sun exposure. Williams (2010) indicates that mildew growth on painted wood siding is most prevalent on walls that remain damp. Walls with direct solar exposure are expected to dry rapidly. Sherwood (1983) reported very low moisture contents at the sheathing/siding interface in south-facing walls installed in this building during warm sunny weather. The spray fences had likewise faced south and were not shaded. On the spray fences where specimens had been installed with intact drip edges, specimens of OSB and of classes 10 through 14 had shown no mildew growth. For specimens of OSB and of classes 10 through 14, there was essentially no difference with regard to mildew growth, between spray fence and building exposure. For the other board classes, which had shown some mildew growth in spray fence exposure, mildew growth was less prevalent on the building than it had been on spray fences.

To identify the presence of fungal colonization that was not visible from board faces, a sample of boards was selected for microscopic inspection of water-stained areas on their backs. Eight board specimens were selected for the sample. Specimens with the widest possible range of back-face staining were selected. Three of the eight specimens had extensive and intense back-face staining; these were specimens of board classes 8 and 14. Five of the eight specimens had distinctly more limited and less intense back-face staining than average. This sample of five specimens contained one class 2 board, one class 7 board, two class 11 boards, and one class 13 board. Observations were made using reflected light microscopy at low magnification, and transmitted light microscopy at various magnifications. Observation was made at the most intensely stained area on the back of each specimen. Significant colonization by mold/stain fungi was observed in the specimens of class 8 and class 14 board. Limited presence of hyphae of decay-type fungi was also observed in these specimens. In contrast, the specimens of board classes 2, 7, 11, and 13 showed limited presence of mold/stain fungi, and no hyphae of decay-type fungi. In

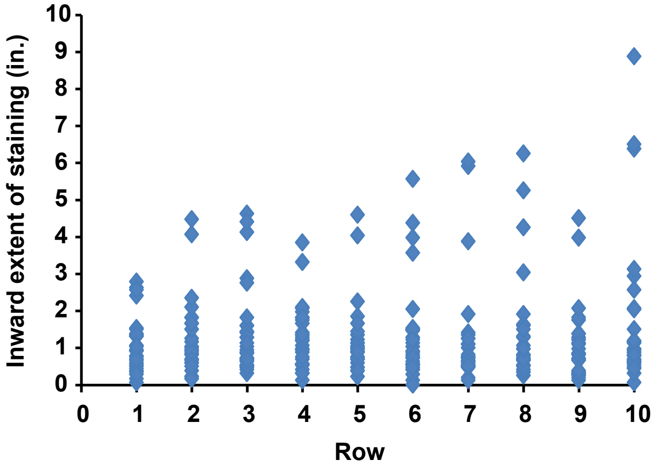

Figure 8. Measurements of inward extents of water stains from board ends, in areas above the lap, by siding course (26 hardboard specimens per course).

summary, microscopic examination indicated that all boards had some degree of fungal colonization by the end of the exposure period, even if minor and essentially inconsequential. The examination also indicated that fungal colonization was more extensive, and potentially more serious, in specimens with more extensive and intense back-surface staining.

Discussion and Analysis

Spatial Variation in Back-Face Staining

Of the 18 boards with perceptible back-surface staining at mid-specimen length, 10 were in bottom-course locations. In all the other siding courses, either no, one, or two specimens had staining at mid-specimen length. The inward extent of back-surface staining from specimen ends also varied with the siding course, with more staining being present in lower siding courses. Some course-dependency of inward extent of staining at board ends (above the lap area) can be seen in Figure 8. In summary, staining on the back surfaces tended to be less extensive on boards in upper courses than on boards in lower courses, and most extensive on boards in the lowest course. The specimen placement scheme, which as mentioned previously assigned two specimens of each of the board classes to each siding course, accommodated for course-dependency of water exposure.

Notably higher water exposure at the lowest siding course might intuitively be explained by splash wetting. As mentioned previously, however, under a set of conditions that were believed to be particularly conducive for splash wetting, a wetted zone was observed that did not quite reach the lowest siding course. The observation suggested that splash wetting was not a major factor in wetting of the lowest siding course. Nevertheless, the possibility of some splash wetting over the 155-month exposure period cannot be dismissed. It is also possible that the open airspace below the building resulted in higher than anticipated wind-driven rain exposure at the lowest siding course. The open airspace resulted in the lowest course of siding being located, from the perspective of wind, near a building edge. Rose (2005, chapter 4, page 122) provides an explanation for concentrated deposition of wind-driven rain at building edges and corners. It is not, however, known if edge effect, associated with the airspace below the building, had a significant effect on wind-driven rain deposition at the lowest siding course.

Progressively greater water exposure on lower courses of siding than on upper courses of siding can be explained by “run-down” wetting (sometimes called “cascade” wetting) by water shed from areas higher on the wall. In addition, during a substantial number of the hours during which there was wind-driven rain with a southerly component, the overhang likely provided shelter preferentially to upper courses of siding.

Correlation of Failure Modes with Laboratory Test Results

As was the case for the portion of the study involving spray fence exposure (Carll and TenWolde 2004), we performed analyses of the relative frequency (or probability) of varying degrees of development of the two observed failure modes, within ranges of (laboratory-measured) RTS. The drip-edge paint crack rating and the welt index rating of each specimen at the end of its building exposure were each placed in a data set along with the average RTS value (determined previously) of two specimens, which had been next to the “building” specimen before specimens had been cut from the strip of material that provided specimens (see fig. 3 of Carll and TenWolde). The analytical methodology involved segregating the data set into “bins” based on average RTS value, and then developing relative frequency plots from the segregated data. An issue in the methodology was selection of bin widths (range of RTS values) such that there was adequate resolution (number of bins) while leaving a sufficient number of data points in the bins such that calculated frequencies for the bins were meaningful. For that reason, we selected a RTS bin range of 10%.

Because boards of class 12 had been mismanufactured, they were not included in these analyses. As mentioned previously, OSB had been included in the study as a reference material, and there was no supposition that test protocols in the American National Standard for hardboard siding might be predictive of field performance of OSB siding. OSB siding was therefore also excluded from these analyses. Table 13 shows the data segregation used to develop the frequency plots.

We found residual thickness swelling to be a reasonably good predictor of the likelihood of a board developing edge welting in service, both for the noncommercial siding (Fig. 9a) and commercial boards (Fig. 9b). We also found it

Table 13. Number of specimens in each RTS bin

RTS bin		Number of specimens per bin	
Center (% RTS)	Range	Noncommercial boards	Commercial boards
5	0–10	61	47
6	1–11	67	55
7	2–12	74	77
8	3–13	77	95
9	4–14	78	96
10	5–15	72	99
11	6–16	59	90
12	7–17	48	81
13	8–18	38	81
14	9–19	30	77
15	10–20	21	69
16	11–21	18	63
17	12–22	13	41
18	13–23	15	25
19	14–24	19	19
20	15–25	19	7
21	16–26	22	6
22	17–27	24	6
23	18–28	27	4
24	19–29	29	4
25	20–30	28	4
26	21–31	28	2
27	22–32	27	1
28	23–33	23	1
29	24–34	19	0
30	25–35	19	0
31	26–36	16	0
32	27–37	14	0
33	28–38	10	0
34	29–39	10	0
35	30–40	9	0
36	31–41	7	0
37	32–42	6	0
38	33–43	5	0
39	34–44	4	0
40	35–45	3	0

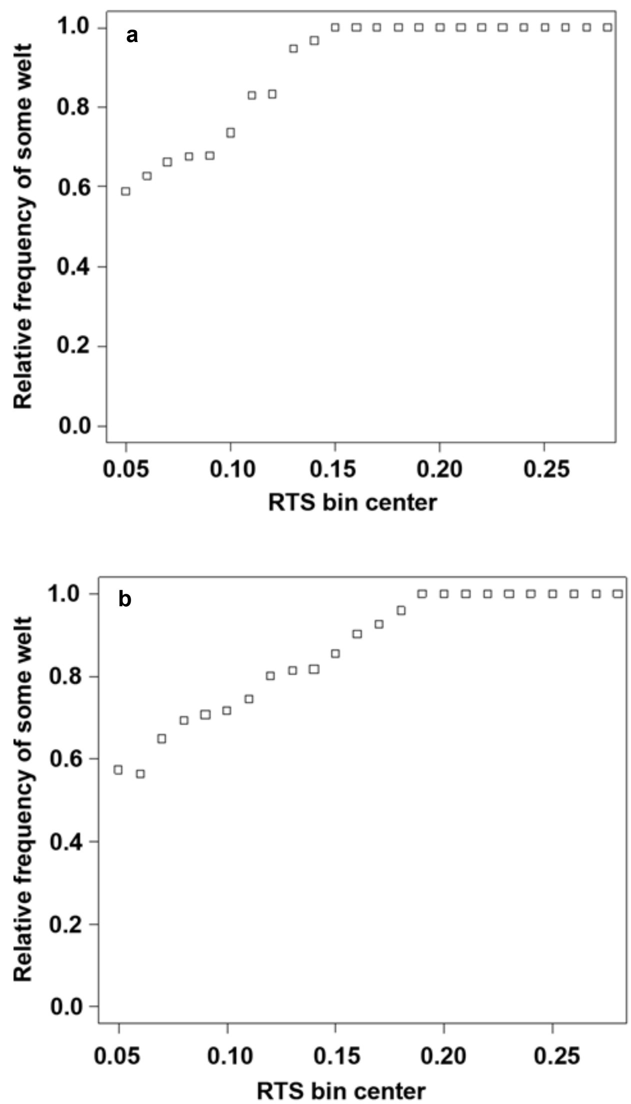

Figure 9b. Relative frequency in 155-month exposure of edge-welt development as a function of residual thickness swell (RTS) of matched specimens in laboratory testing; (a) noncommercial hardboard sidings, (b) commercial hardboard sidings.

to be a reasonably good predictor for the development of high levels of either drip-edge paint cracking or edge welting in service (Figs. 10a, b and 11a, b, respectively). These findings largely correspond with what was observed previously in spray fence exposure (Carll and TenWolde 2004). Figures 9 and 11 indicate a continual improvement in welt performance as RTS value decreased. The figures indicate no value below 20% RTS, (or for that matter 17% RTS), beyond which further decreases in RTS value were not associated with higher relative frequency of improved welt performance. In a similar manner, Figure 10a indicates that below a bin center value of roughly 17% RTS, performance of noncommercial boards with respect to drip-edge paint cracking continually improved with reduction (lowering) of RTS value. In contrast, while Figure 10b indicates a trend of improved performance with respect to drip-edge paint cracking with improved (lowered) RTS value, it also indicates that the relative frequency of significant or severe drip-edge paint cracking was not lowered as bin center value fell below 9% RTS. Figure 10b also indicates that the relative frequency of intact or nearly intact drip edges did not increase as bin center value fell below 9% RTS.

As indicated previously, the 17% RTS criterion value promulgated in the 2006 revision of the American National Standard represented a reduction in the criterion value (the establishment of a more stringent requirement) than in previous versions of the standard. In spray fence exposure, there was no “plateau” value for RTS below which edge-welt performance or drip edge paint cracking did not continue to improve. In building exposure, a similar trend

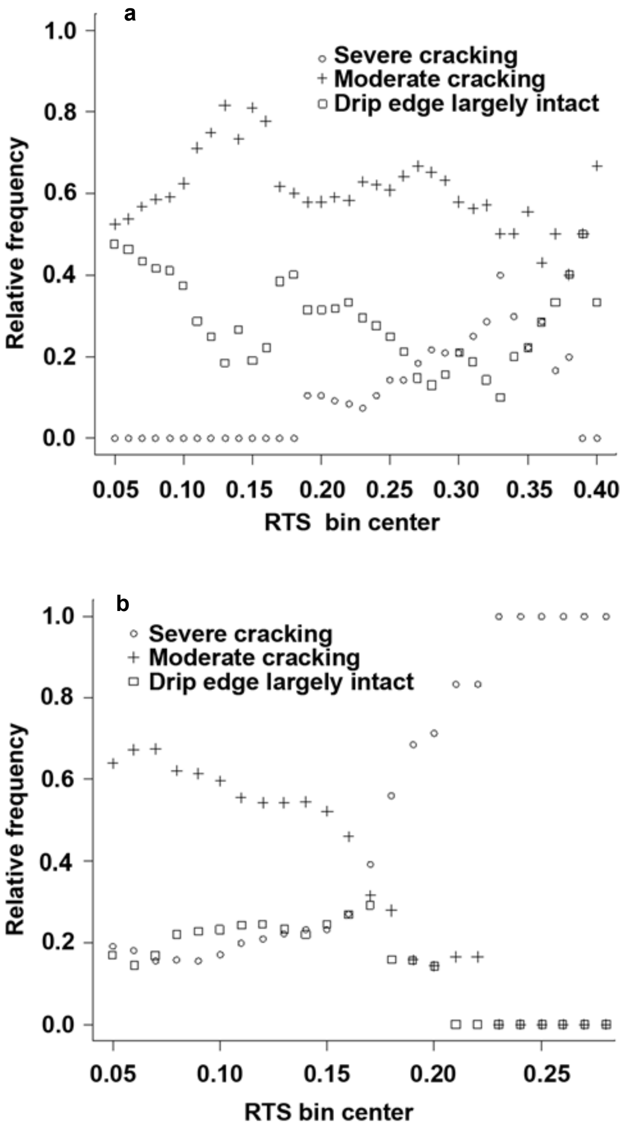

Figure 10. Relative frequencies in 155-month exposure of three different levels of drip-edge paint cracking as a function of residual thickness swell (RTS) of matched specimens in laboratory testing; (a) noncommercial hardboard sidings, (b) commercial hardboard sidings. Legends have abbreviated text: squares indicate drip edges in intact or largely intact condition, crosses indicate drip-edge paint cracking ranging from minor to moderate, and circles indicate paint cracking ranging from significant to severe. A specimen with drip-edge paint cracking restricted to board ends would have been classified as intact.

(lack of "plateau" value) was observed with regard to welt performance, and was sometimes observed with regard to drip-edge paint cracking. In the case where there was an apparent "plateau" value for RTS, below which further reduction in RTS did not result in improved performance with regard to drip-edge paint cracking, the plateau value was at 9% RTS, (well below the 17% criterion in the 2006 revision of the Standard). Carll and TenWolde (2004) made three recommendations; two related to statistical confidence in test results, while the third was that the pass-fail criterion be lowered (from 20% RTS) "to 17% or lower." Of these recommendations, only the recommendation to lower the RTS criterion to 17% was adopted in the 2006 revision of the Standard. To summarize, in both spray fence and building exposures, with regard to the two common failure modes, there typically was continual improvement in performance as RTS value decreased. In the one case where continual improvement over the entire range of RTS values was not observed (performance with regard to drip-edge paint cracking of commercial boards in building exposure) there was improvement as RTS value decreased until it reached a value of well below the current criterion level in the Standard. Improved in-service performance would thus be expected if the criterion level in the Standard were to be lowered to a value well below its current (17%) level.

Edge Welting—Association with Drip-Edge Paint Cracking

As discussed in the Results section of this paper, drip-edge paint cracking typically preceded development of edge welting. As also indicated in the Results section, welt behavior was, without exception, substantially worse for specimens exposed (in the earlier part of this study) on spray fences with painted drip edges removed than it was in specimens exposed on spray fences with painted drip edges, or than it was (in this portion of the study) in building exposure. This suggests that maintenance of an intact paint film on drip edges is a requisite for avoiding edge-welt development in hardboard siding.

Class 10 board was anomalous relative to other board classes in two regards:

- It showed marginally poorer welt performance (see Results section) on the building than it had when installed on a spray fence with a painted drip edge, whereas all other board classes showed better welt performance on the building than on the spray fence.
- It showed the lowest average RTS values in substrate weatherability testing (Table 3), but at the end of building exposure showed, on average, a poorer welt index value than boards in classes 1, 2, 11, 13, or 14 (Table 8). This contrasts with the general trends indicated by Figures 9 and 11.

Each of these anomalous behaviors can be explained in terms of drip-edge condition. When viewed from this perspective, the welt behavior of class 10 board relative to other board classes was reasonably similar across the exposures (accelerated or nonaccelerated). Class 10 board had shown a lower (better) average welt index value than any other board class in accelerated (fence) exposure when installed with intact drip edges, but, relative to other board classes, had shown unimpressive welt performance when painted drip

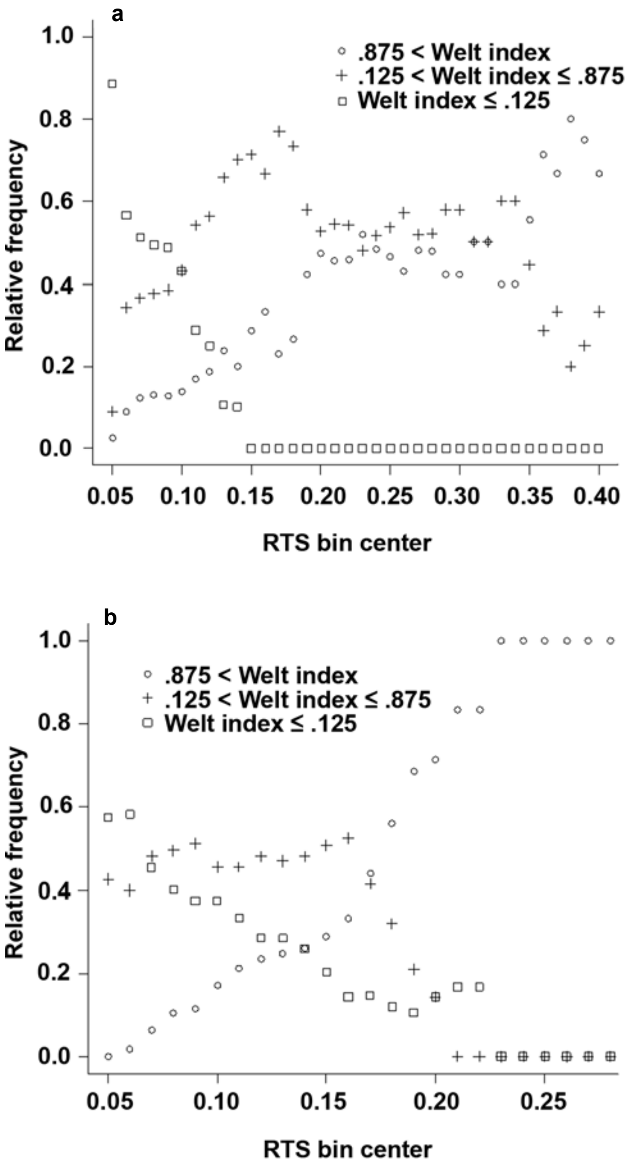

Figure 11b. Relative frequencies in 155-month exposure of three different levels of edge-welt index in as a function of residual thickness swell (RTS) of matched specimens in laboratory testing ; (a) noncommercial hardboard sidings, (b) commercial hardboard sidings.

edges had been cut off (Carll and TenWolde 2004). In a similar manner, class 10 boards showed good welt performance during roughly the first half of the 155-month exposure period, but unimpressive welt performance during the later stages of the period. In the later stages of the exposure period, drip-edge paint cracks had been present in most class 10 boards for a number of years, whereas in board classes 1, 2, 11, and 13 drip-edge paint cracking was relatively rare (Table 6). Drip-edge cracking in class 10 boards was restricted to layers very close to the specimen face, which coincidentally, were the layers of highest density (Table 4). In class 10 board, in particular, swelling of layers very close to the surface was an apparent factor in initiation of drip-edge paint cracking, even though overall thickness swelling for this class of board was low.

Initiation of Drip-Edge Paint Cracking

Drip-edge paint cracking occurred in a majority, or a significant minority, of specimens of most classes of commercial board by 6 years of exposure (column for September 2003 in Table 8). A significant minority of specimens of the poorer classes of noncommercial board also showed drip-edge paint cracking by 6 years of exposure. Drip-edge paint cracking moreover occurred even though there was no measurable increase in in-service thickness (Fig. 6). This suggests that fluctuations in board thickness that were of fairly modest magnitude were sufficient to initiate paint cracking at drip edges.

As indicated previously, there is indication that water intrusion into lap areas was occasionally a factor in initiation of drip-edge paint cracks (in some specimen of board classes 5, 6, and 14), but in most cases was not a factor in initiation of drip-edge paint cracking. The majority of specimens showed no water staining in lap areas (Tables 5 and 6), yet most developed drip-edge paint cracks (Table 8). The bulk of drip-edge paint cracking initiated near the mid-length of specimens (away from board ends), and the distances by which back-surface stains at drip edges extended from board ends (Table 6) were typically far short of specimen mid-length. Finally, the most prevalent location for drip-edge cracks was toward the front of the specimen (Table 10), not at the location (near the back of the specimen) where water that intruded into specimen laps would have been present. In most cases, something other than water intrusion into lap areas must have been responsible for initiation of drip-edge paint cracking. The likely explanation is penetration of the paint film by modest amounts of water, near the interface of the drip edge and the specimen's front surface. Initiation of drip-edge paint cracking at this location is shown in Figure 12. The interface of the drip edge and the face was a common location for initiation of drip-edge paint cracking.

Thickness swelling of wood composition panels, on a unitized basis, invariably exceeds along- or across-panel dimensional change. In addition, unitized layer thickness swelling in wood composition panels varies with layer position, typically being greatest in surface layers (Xu and Winistorfer 1995). The intersection of the drip edge with the board surface can therefore be viewed as a location where there is a considerable change (a local discontinuity) in dimensional stability of the substrate. At this location, paint films can thus be expected to undergo particular strain when there is a change in moisture content of the underlying board. An imperfection in the paint film at this location could provide a pathway for water penetration of the film, providing conditions for initiation of a paint crack. The micrographs taken for measurement of paint film thickness

Figure 12. Magnified image showing initiation of cracking at the interface of the drip edge and the outer specimen face in a specimen of class 2 board. With the exception of these observed cracks, some cracking near the unpainted end cuts, and some surface dirt, the specimen was in pristine condition after 155 months of exposure. This specimen did not have a shaped drip edge, inasmuch as it was a specimen of noncommercial board.

indicated substantial variation in film thickness on drip edges (much more so than on specimen faces), with much of the variation being localized, and associated with unevenness of the substrate surface. Projecting fibers or fiber fragments were commonly present on drip-edge surfaces, which protruded partially (and occasionally completely) through the paint film.

In the micrographs taken for measurement of paint film thickness, a thinning of the paint film at the very intersection of the face and the drip edge was also commonly observed. This localized thinning of the paint film tended to be more noticeable in the noncommercial boards (classes 1–6), which as indicated previously, did not have shaped drip edges. This might logically have been expected to result in more extensive or severe drip-edge paint cracking in noncommercial boards than in commercial boards, but Table 8 generally indicates the opposite. We hypothesize that a combination of the dimensional properties of the substrate at the drip edge (and in particular a discontinuity in these properties at the interface of the drip edge and the face) with the presence of projecting fibers at the drip edge (which resulted in variable effective coating thickness) explains the pattern of paint performance we observed (essentially perfect performance on board faces, while cracking on drip edges was widespread, and was sometimes severe).

That average initial topcoat paint film thickness (approximately 1.5 mils) was roughly half of what is commonly recommended, was almost certainly a factor in penetration of the paint film at the drip edge by water, and in turn, to initiation of drip edge paint cracking.

Conclusions

The failure modes observed in 155 months of exterior exposure in Madison, Wisconsin, were development of drip-edge paint cracks, followed by development of edge welting. The extent and severity of these failure modes varied considerably by board class. Considerable variation between board classes was observed for both noncommercial and commercial boards. Inasmuch as development of drip-edge paint cracks preceded development of edge welting, drip-edge paint cracking was the most prevalent failure mode at the end of 155-month exposure. In this study, initiation of drip edge paint cracking was, in most cases, evidently associated with water penetration of the paint film at the drip edge.

Paint film on specimens was substantially thinner than recommended. On board faces, thinness of the paint film did not seem to matter, inasmuch as paint condition on board faces remained essentially perfect. On drip edges, however, thinness of the paint film was almost certainly a factor in initiation of drip edge paint cracking. One of the classes of noncommercial board performed nearly flawlessly, indicating its ability to withstand long-term exposure despite thinness of the paint coating, even on drip edges.

Open end joints evidently resulted in water entry behind siding at specimen ends, but in most cases did not appear to be a significant factor in development of drip-edge paint cracks nor in subsequent edge-welt development. This is probably because the exposure site was evidently less challenging (experienced less rainfall) than most exposure sites in the eastern states, and that water entry into the open end joints was largely restricted to water that entered them directly as wind-driven rain. The amounts of water that could enter open end joints along window casings might be expected to be considerably higher, particularly where window head flashings are imperfectly selected or installed, potentially spilling water into the joints from substantial watershed areas.

Back-surface water staining indicated that water exposure was greater on lower than on higher courses of siding. The stain patterns also suggest that capillary rise did not occur at siding laps. For most of the classes of hardboard siding there was evidence that water entering open end joints, and thus present on the board rear surface, was not drawn by capillary suction into siding laps.

Relative frequency of the two failure modes observed was related to residual thickness swelling (RTS) value of the board, as identified by the substrate weatherability test procedure in the American National Standard for hardboard siding. Specimens in exterior exposure whose matched laboratory test specimens had lower RTS values generally performed better. Lower RTS values were associated with lower relative frequency of failure and lower relative frequency of more intense failure. In most cases, there was no “plateau” value below which further reductions in RTS were not associated with greater relative frequency of improved in-service performance.

Although the degree to which failures occurred in accelerated exterior exposure was typically greater than the degree to which they occurred in long-term (nonaccelerated) exterior exposure, the relative degrees, between board classes, to which they occurred were similar. Stated another way, the findings of Carll and TenWolde (2004), which were based on accelerated exposure, were found to largely be applicable to long-term exposure.

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Appendix—Rainfall and Scheffer Index Values for One Location in Each State East of and Immediately West of the Mississippi River

Location	Scheffer Index (1990–2009)		Annual rainfall (1990–2009)		
	Mean value	COV (%)	Mean (in.)	Mean (mm)	COV (%)
Albany, NY	53	17	34	880	17
Baltimore, MD	58	22	41	1050	17
Baton Rouge, LA	89	15	56	1430	19
Boston, MA	50	13	37	930	17
Burlington, VT	56	15	28	720	25
Charleston, WV	74	14	40	1020	7
Columbia, SC	72	18	44	1120	22
Concord, NH	47	16	35	890	23
Dayton, OH	56	16	40	1010	18
Des Moines, IA	51	17	34	850	25
Hartford, CT	53	18	44	1130	15
Indianapolis, IN	57	16	41	1040	18
Jackson, MS	73	19	54	1380	15
Lansing, MI	46	9	28	710	16
Little Rock, AR	62	21	46	1160	24
Louisville, KY	64	16	45	1150	14
Macon, GA	72	19	46	1170	17
Memphis, TN	65	17	55	1400	21
Minneapolis, MN	46	18	25	640	17
Montgomery, AL	71	18	48	1210	19
Newark, NJ	61	19	43	1090	14
Peoria, IL	49	20	35	880	27
Pittsburgh, PA	59	14	35	890	20
Portland, ME	43	16	42	1060	24
Providence, RI	49	18	44	1110	13
Raleigh, NC	71	13	43	1100	17
Richmond, VA	65	20	43	1100	20
St. Louis, MO	56	16	39	980	20
Tampa, FL	99	12	46	1180	22
Wilmington, DE	56	24	42	1080	15