Fifty-Year Durability Evaluation of Posts Treated with Industrial Wood Preservatives

Stan Lebow Patricia Lebow Bessie Woodward
Grant Kirker Rachel Arango

Abstract

Long-term durability data are needed to improve service life estimates for treated wood products used as critical structural supports in industrial applications. This article reports the durability of longleaf pine (*Pinus palustris*) posts pressure treated with ammoniacal copper arsenate (ACA), chromated copper arsenate (CCA), creosote, or pentachlorophenol and exposed for 50 years in southern Mississippi. During inspections, posts were subjected to a pass/fail evaluation by applying a load to the top of the post. No failures occurred in any of the 125 posts treated with CCA or in any of the 75 posts treated with pentachlorophenol. Three of 25 ACA-treated posts and 5 of 25 creosote-treated posts failed. Estimated times to 50 percent failure in the ACA- and creosote-treated posts were calculated as 96 and 78 years, respectively. The estimated years to failure for the CCA- and pentachlorophenol-treated posts could not be calculated because of the lack of failures but presumably would be greater than that calculated for the ACA- and creosote-treated posts. The durability of the posts is notable because the exposure site presents a severe biodeterioration hazard. The results of this study indicate that in-service posts, poles, and piles treated to standardized retentions with these industrial preservatives will be highly durable.

Pressure-treated wooden poles, piles, and posts are commonly used for a range of industrial applications, including those that are structurally critical. Long-term resistance to biodeterioration is a key characteristic of these materials, but relatively little information has been published that documents their expected service life. The need for service life estimates has increased in recent years as the use of life-cycle cost analysis (LCCA) to evaluate alternative construction materials has become more commonplace (US Department of Transportation 2002, Al-Wazeer et al. 2005). Emphasis on use of green building materials has also increased interest in conducting life-cycle assessments (LCAs) to compare the environmental impact of treated wood with those of alternative materials (Bolin and Smith 2011). Service life estimates are a key part of evaluating these potential environmental impacts.

The paucity of published service life data for preservative-treated structural members can result in durability estimates that appear overly conservative. For example, reports prepared as part of an evaluation of replacement options for a historic wooden drawbridge concluded that wooden piling would last only 20 to 30 years (URS Corporation 2011a, 2011b). This relatively short service life estimate was at odds with the performance of the bridge's existing creosote-treated piles, many of which had remained in service since 1925. The authors expressed concern that piles treated with noncreosote preservatives would not be nearly as durable as the existing piles (URS Corporation 2011a). Similarly, a report prepared for the National Marine Fisheries Service used an estimated service life of only 15 years for treated piles (NOAA Fisheries 2009). This 15-year life estimate led the authors to conclude that treated wood piles, despite their lower initial cost, would have little cost advantage over alternative construction materials that were perceived to have a longer service life. Utility personnel also appear to have relatively low expectations for the service life of treated poles. Stewart (1996) noted that his survey group reported an average perceived pole service life of only 33 years, while the replacement rate data indicated a service life in excess of 75 years. Similarly, Morrell (2008) noted that based on reported replacement rates, pole service life would easily reach 80 years in many parts of the United States. Australian researchers conducted a statistical anal-

The authors are, respectively, Research Forest Products Technologist, Research Mathematical Statistician, Microbiologist, Research Forest Products Technologist, and Entomologist, USDA Forest Serv., Forest Products Lab., Madison, Wisconsin (slebow@fs.fed.us [corresponding author], plebow@fs.fed.us, bwoodward@fs.fed.us, gkirker@fs.fed.us, rarango@fs.fed.us). This paper was received for publication in January 2015. Article no. 15-00002.

Forest Prod. J. 65(7/8):307–313.
doi:10.13073/FPJ-D-15-00002

ysis of utility pole service life data and concluded that the expected service life of the poles would be in the range of 80 to 95 years (Mackisack and Stillman 1996). A limitation of these service life estimates based on pole replacement rates, however, is that poles are often replaced due to causes other than biodeterioration, such as road construction or storm damage.

Additional detailed and preservative-specific service life data are needed to improve the precision of LCCA and LCA estimates. One source of durability data is the field tests used to develop and evaluate wood preservatives. These tests typically use stakes with relatively small dimensions to shorten the time needed for testing, and it is often unclear how the durability of small stakes corresponds to the expected service life of commodity-sized material (American Wood Protection Association [AWPA] 2013a). In some cases, however, long-term tests using larger posts are established by universities and government agencies. The USDA Forest Service's Forest Products Laboratory (FPL) established numerous tests of post durability during the early and middle 20th century. One of these plots, established in 1964 within the Harrison Experimental Forest in Mississippi, includes posts pressure treated with creosote, pentachlorophenol, chromated copper arsenate (CCA), and ammoniacal copper arsenate (ACA). The conditions at this site present a severe decay and termite biodeterioration hazard; therefore, long-term durability at this location indicates the potential for similar or even greater durability at most other locations in North America. This article summarizes the 50-year durability of these posts and discusses the implications for the expected service life of treated commodities.

Materials and Methods

Post preparation and preservative treatment

The posts used in this study were longleaf pine (*Pinus palustris*), a member of the southern pine species group. They were cut near Brewton, Alabama, and then peeled and kiln dried to 17 ± 2 percent moisture content before shipment to the FPL. The posts were cut to a uniform length of 1.83 m (6 ft) before preservative treatment. The top (small-end) diameter of the posts was generally in the range of 102 to 152 mm (4 to 6 in.). Thirty-five replicate posts were pressure treated with respective preservatives as shown in Table 1. Each post was weighed before and after treatment, and this weight gain was multiplied by the solution concentration to estimate the retention of preservative active ingredient in the posts (creosote is considered to be 100% active). Samples for chemical analysis (assay) were removed from 10 posts per treatment group, leaving 25 replicates per treatment for installation at the test site. The assay samples removed from the posts were composited to obtain a single assay retention value for each set of posts; thus, no measure of variability is available for the assay analysis. Details of the analysis methods are not available for this study, but based on other FPL research at that time, creosote retention likely was determined by toluene extraction and pentachlorophenol by lime ignition, in a manner similar to current AWPA methods A6-09 and A5-11, respectively (AWPA 2013b, 2013c). Copper, chromium, and arsenic analyses likely were conducted using wet ashing (digestion) with subsequent titrations in a manner similar to current AWPA method A2-11 (AWPA 2013d). Assay retentions tended to be slightly greater than those calculated by weight gain (Table 1). This is not surprising as the weight gain retention is calculated on the entire post volume, including the untreated heartwood, while only the treated sapwood is included in the assay analysis. Inspection of the posts removed for assay indicated that the posts generally had 100 percent preservative penetration of the sapwood. The ranges of retentions standardized for preservative-treated wood in contact with the ground are shown for comparison in Table 2.

Table 1.—Preservative treatments and retentions in test posts.

Preservative[a]	Preservative retentions in wood (kg/m^3)[b]				
	Weight gain retention				By chemical analysis
	Mean	Max.	Min.	SD	
ACA (ACZA)	8.01	9.37	7.07	0.57	8.32
CCA-A	7.00	7.58	6.53	0.30	8.00
CCA-B	7.76	8.52	6.99	0.46	10.24
CCA-B	6.13	12.96	5.33	1.46	7.04
CCA-C	6.78	7.52	5.95	0.37	8.64
CCA-C	7.03	7.54	6.45	0.35	9.28
Creosote	133.12	156.80	107.20	16.10	137.60
Pentachlorophenol-1	6.36	7.52	5.60	0.56	6.88
Pentachlorophenol-2	6.68	7.92	5.20	0.89	7.68
Pentachlorophenol-2W	6.45	7.60	5.20	0.75	6.88

[a] ACA = ammoniacal copper arsenate; ACZA = ammoniacal copper zinc arsenate; CCA = chromated copper arsenate (type A, B, or C).

[b] For retentions in pounds per cubic foot (lb/ft^3), divide the values by 16.

Preservative treatments evaluated

The test plot contains CCA, creosote, pentachlorophenol, and ACA preservative treatments. The test plot also contains other types of preservative treatments that are not discussed in this report because of their lack of direct relevance to current preservatives.

Chromated copper arsenate.—CCA-treated (or ''green-treated'') wood has been widely used since the early 1940s, and it was the most widely used type of treated wood from the 1970s through the early 2000s. Multiple formulations have been used, and these formulations are characterized by slightly different proportions of chromium trioxide, copper oxide, and arsenic pentoxide. Three formulations (types A, B, and C) were standardized by the AWPA, but eventually, CCA-C became the predominate formulation that is currently used for treatment of poles, piles, and heavy timbers. At the time this post study was initiated, several CCA formulations were in use, and FPL researchers chose to evaluate five formulations that bracketed the component ratios used commercially at that time. Two of the formulations are nearly identical to the current CCA-C, while two others are similar to CCA-B and one represents CCA-A (Table 1). The retentions of the CCA-A and CCA-C formulations evaluated in this study (Table 1) are similar to those standardized for treatment of posts (Table 2) but below those standardized for treatment of poles and piles. Based on assay analysis, the CCA-B retention meets the minimum retention specified for posts and poles but is below that specified for piles.

Creosote.—Creosote, one of the oldest wood preservatives, is a black or brownish oil made by distilling the tar that is obtained after high-temperature carbonization of coal. Creosote continues to be widely used for treatment of

*Table 2.—American Wood Protection Association (AWPA) standard retentions for pressure-treated longleaf pine (*Pinus palustris*) used in ground-contact applications (AWPA 2013g).*

	Retention (kg/m^3) by commodity type and AWPA use category[b]								
	Timbers			Posts		Poles			Land piles
Preservative[a]	UC4A	UC4B	UC4C	UC4A	UC4B	UC4A	UC4B	UC4C	UC4C
ACZA (replaced ACA)	6.4	9.6	9.6	6.4	8.0	9.6	9.6	9.6	12.8
CCA-C	6.4	9.6	9.6	6.4	8.0	9.6	9.6	9.6	12.8
Creosote	160	160	192	128	160	96	120	144	192
Pentachlorophenol	8.0	8.0	8.0	6.4	8.0	4.8	6.1	7.2	9.6

[a] ACZA = ammoniacal copper zinc arsenate; ACA = ammoniacal copper arsenate; CCA-C = chromated copper arsenate type C.
[b] Use categories (UC) designate the type of service condition: 4 = wood will be in contact with the ground or fresh water; A = general use; B = heavy duty use; C = extreme duty application. For example, UC4A indicates general use wood that will be in contact with the ground or fresh water.

poles, piles, bridge timbers, and railroad ties. One set of creosote-treated posts was included in the post plot reported here. The retention evaluated (Table 1) is similar to those standardized for general use posts and poles (Table 2) but below that specified for piles or for posts in applications with a high decay hazard.

Pentachlorophenol.—Pentachlorophenol has been used since the 1940s for the treatment of poles, terrestrial piles, timbers, and glued-laminated beams. Pentachlorophenol can be dissolved in either ''heavy'' (similar to No. 2 fuel oil) or ''light'' (similar to mineral spirits) solvents. Use of the heavy solvent is typical for ground-contact applications, and in this article, discussion is limited to posts treated with the heavy solvent. In this study, three groups of 25 posts each were treated with pentachlorophenol in heavy solvent described as meeting the properties for ''Type A'' as specified in the AWPA Standard P9-10 (AWPA 2013e). Two groups (referred to as pentachlorophenol-1 and pentachlorophenol-2) differed only in that the oil was sourced from different suppliers (American Petrofina and Shell Oil, respectively). The third group (referred to as pentachlorophenol-2W) utilized the same oil as the pentachlorophenol-2 group but also included 10 percent paraffin wax. The retentions evaluated (Table 1) are similar to those standardized for general use posts and poles but below that specified for piles or for posts in applications with a high decay hazard (Table 2).

Ammoniacal copper (zinc) arsenate.—ACA was used commercially, primarily on the west coast of the United States and Canada, from the 1930s to the 1990s. It was then replaced with ammoniacal copper zinc arsenate (ACZA), which is the current commercial formulation and appears to be at least as effective as ACA (Best and Coleman 1982). The post plot reported on here included ACA-treated posts, and these data will be discussed because of their relevance to the current ACZA formulation. The retention evaluated in this study (Table 1) is similar to that standardized for ACZA treatment of posts (Table 2) but below those standardized for treatment of poles or piles.

Post installation

The posts were installed in 1964 within the Harrison Experimental Forest (near Saucier, Mississippi). The site is forested, with Poarch fine sandy loam soil and average annual rainfall of 1.57 m (62 in.). The location has a warm, moist climate that favors attack by both termites and decay fungi and falls within AWPA Deterioration Zone 5 (severe exposure; AWPA 2013f). Posts were assigned locations within the test plot using a randomized block method in which the plot was divided into 25 blocks, each containing one post from each treatment and one untreated control post. The posts were set to a depth of 0.61 m (2 ft) with 0.91 m (3 ft) spacing between posts.

Post evaluation

The condition of the posts was evaluated at 1- to 2-year intervals from 1965 to 1990, but no evaluations were conducted between 1990 and 2014. At each inspection, the posts were either given a ''push'' or ''pull'' or subjected to a 22.7-kg (50-lb) load applied to the top of the post using a spring scale. The 22.7-kg (50-lb) loading method was utilized for the 2014 inspection. Posts were listed as ''passing'' or ''failing'' depending on whether they withstood the loading. Whenever possible, posts that had failed between the 1990 and 2014 inspections were located and identified. However, some posts could not be located and were deemed ''missing'' (Table 3). These posts may have failed and completely decomposed before 2014 or were sound posts that were crushed under fallen trees. Several hurricanes impacted the test site between the 1990 and 2014 inspections, causing mature trees to fall into the plot. ''Pilfering'' has also been reported as a possible cause of missing posts at this test site (Davidson 1977), although there is no direct evidence of such activity for posts in the current study.

Table 3.—Number of failures observed in treated posts over 50 years of testing.

Preservative[a]	No. (%) failed	No. missing[b]	Years (no. of failures)
ACA (ACZA)	3 (12)	1	1990 (2), 2014 (1)
CCA-A	0 (0)		
CCA-B	0 (0)		
CCA-B	0 (0)		
CCA-C	0 (0)		
CCA-C	0 (0)		
Creosote	5 (20)	1	1988 (1), 2014 (4)
Pentachlorophenol-1	0 (0)		
Pentachlorophenol-2	0 (0)	1	
Pentachlorophenol-2W	0 (0)	1	

[a] ACA = ammoniacal copper arsenate; ACZA = ammoniacal copper zinc arsenate; CCA = chromated copper arsenate (type A, B, or C).
[b] Number of posts passing at the 1990 inspection but missing at the 2014 inspection.

For the treatment groups with failures (ACA and creosote), a statistical analysis was conducted to characterize the expected longevity of the posts. The data were analyzed assuming an interval-censored Weibull lifetime distribution and calculating approximate 90 percent confidence intervals on estimated years to failure (Meeker and Escobar 1998). Most observations were right censored with the last inspection exposure time as the lower bound, the missing observations right censored with the last known inspection exposure time, and failed observations interval censored with the last passed inspection exposure time as the lower bound and the failed inspection exposure time as the upper bound. Because failures were minimal and similar previous research indicated Weibull failure patterns (Freeman et al. 2005), Weibull distributions were assumed. Final models appeared satisfactory. The approximate confidence intervals are quite wide, however, and extrapolations should be considered with caution. Analysis was conducted using SAS version 9.4 software in proc LIFEREG to obtain maximum likelihood estimates and confidence intervals.

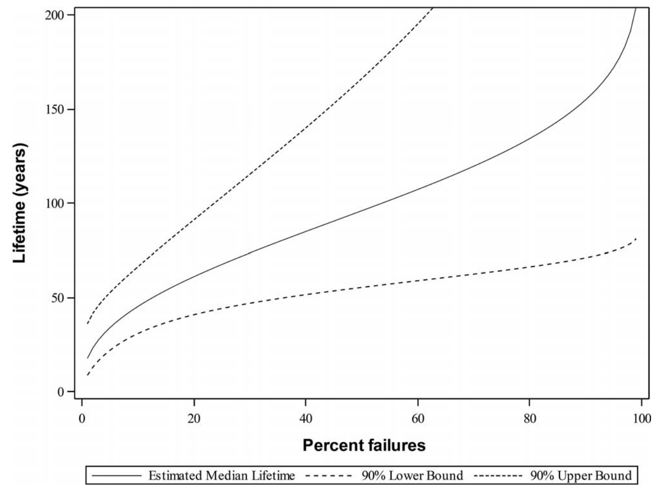

Figure 1.—Approximate 90 percent confidence intervals on estimated lifetime for a given percentile of failures in ammoniacal copper arsenate–treated posts.

Results and Discussion

ACA-treated posts

Three of the 25 ACA-treated posts failed during the 50 years of exposure (Table 3). Two of those failures occurred at the 1990 evaluation, and a single failure occurred at the 2014 evaluation. Failure of two posts after 26 years followed by only one additional failure at 50 years is a somewhat unusual pattern and may suggest that the two early failures were a result of poor treatment. However, both early failure posts had fairly typical preservative retentions (based on weight gain during treatment). One additional ACA-treated post was missing as of the 2014 inspection. The missing post probably either failed and decomposed during the 24 years between the 1990 and 2014 inspections or was pinned beneath large trees that fell at the site. Depending on the fate of the missing post, either 12 or 16 percent of ACA-treated posts failed. This compares favorably with the 52 percent failure rate reported for ACA-treated posts after 53 years of exposure in an earlier test plot at the same location (Freeman et al. 2005). However, those earlier posts were treated to an average retention of only 5.4 kg/m^3, which is below the retentions specified for wood used in contact with the ground (Table 2).

Based on the observed failure pattern, the estimated years to failure for a given percentile of the population was calculated (Fig. 1). For example, the estimated years to failure for the first 10 percent of the posts is 45 years, with lower and upper 90 percent confidence limits on that estimate of 31 and 66 years, respectively (Table 4). A much longer time period, 96 years, is estimated for failure of 50 percent of the posts. The lower and upper confidence limits on this 50th percentile are 55 and 166 years, respectively. Note that the confidence limits on these estimates are rather wide because of the limited number of failures and the lack of inspections between 1990 and 2014. These years-to-failure estimates bode well for the durability of wood products treated to standard retentions with the current ACZA formulation, considering that the standard retentions for critical members are greater than those evaluated in the current study.

CCA-treated posts

No failures occurred in any posts treated with CCA formulations (Table 3), and none of the CCA-treated posts were missing at the 2014 inspection (Table 3). Because no failures have yet occurred, it is not possible to estimate the years to failure for the CCA-treated posts.

Previous reports also indicate that posts treated with CCA formulations are highly durable. No failures were observed in a set of 91 CCA-treated posts exposed for 35 years at the same location (Lebow et al. 2014). The retentions of those posts ranged from 3.52 to 16.82 kg/m^3 (0.22 to 1.05 lb/ft^3), with the majority of the retentions in the range of 8.0 to 14.4 kg/m^3 (0.5 to 0.9 lb/ft^3). In a study conducted near Petawawa, Ontario, no failures have occurred after 57 years for jack pine (*Pinus banksiana*) posts treated with CCA-A to an average retention of only 5.1 kg/m^3 (0.32 lb/ft^3; Morris et al. 2012).

Creosote-treated posts

Five of the 25 creosote-treated posts have failed (one in 1988 and four in 2014), and one post could not be located at the 2014 inspection (Table 3). This represents a failure rate of either 20 or 24 percent, depending on the fate of the

Table 4.—Estimated years to failure for ammoniacal copper arsenate (ACA)– and creosote-treated posts at various failure percentiles.

Preservative[a]	Percentile	Estimated years	90% confidence interval (y)	
			Lower	Upper
ACA	10	45	31	66
ACA	25	68	44	103
ACA	50	96	55	166
ACA	63[a]	111	60	205
Creosote	10	37	26	51
Creosote	25	55	40	74
Creosote	50	78	52	116
Creosote	63[a]	90	56	143

[a] The ''characteristic life,'' which is often the value reported for a Weibull distribution, is the 63.2 percentile (Mackisack and Stillman 1996).

missing post. Based on the five known failures, the estimated years to a given percentile of failures are shown in Figure 2. The estimated years to failure for the first 10 percent of the posts is 37 years, with lower and upper 90 percent confidence limits on that estimate of 26 and 51 years, respectively (Table 4). The estimated years to failure for the 50th percentile is 78 years, with lower and upper 90 percent confidence limits of 52 and 116 years, respectively. As was noted for the ACA-treated posts, the confidence limits on these estimates are wide because there have been few failures and no inspections were conducted between 1990 and 2014.

The durability of creosote-treated posts in the current study is similar to that reported for posts exposed in South Carolina. In that study, posts treated with creosote retentions ranging from 64 to 128 kg/m^3 (4 to 8 lb/ft^3) had an approximate failure rate of 30 percent after 50 years of exposure (Webb et al. 2010). A much higher percentage failure for creosote-treated posts (65%) in Mississippi was reported after 53 years of testing in an earlier study (Freeman et al. 2005), but those posts were treated to an average retention of only 89.6 kg/m^3, which is well below the minimum retention for creosote-treated wood used in contact with the ground and less than half of that required for piling (Table 2).

The Mississippi test site utilized in the current study represents a severe deterioration hazard, and greater durability has been reported for creosote-treated posts exposed in areas of North America with lower decay hazard. Red pine (*Pinus resinosa*) posts thermally (non-pressure) treated with creosote have had no failures after 71 years exposure near Petawawa, Ontario, while only one failure has occurred in similarly treated jack pine posts (Morris et al. 2012). No failures have occurred in sawn Douglas-fir posts pressure treated with creosote formulations and exposed for 73 years near Corvallis, Oregon (Morrell 2012).

Pentachlorophenol-treated posts

No failures have been observed in any of the pentachlorophenol-treated posts, although two of the total 75 posts were missing at the 2014 inspection. Given the durability of the remaining posts, the missing posts are unlikely to have failed and completely decomposed between 1990 and 2014. It appears more likely that the missing posts were either concealed under fallen trees or lost to other causes. Some failures (7 of 25 posts) were reported for an earlier installation of pentachlorophenol posts that had been in place for 53 years (Freeman et al. 2005). Those posts were treated to a lower average retention of 5.1 kg/m^3, but the finding of seven failures within 53 years is notable considering that the lowest standardized retention for pentachlorophenol used in contact with the ground is 4.8 kg/m^3 (0.3 lb/ft^3; Table 2). It is worth noting that stakes (38 by 89 by 457 mm in length) treated with pentachlorophenol have been highly durable after 39 or 45 years of exposure at this test site, with no failures in stakes treated to any of the AWPA standardized retentions. This finding extends to one treatment group that was treated to only 4.6 kg/m^3 (0.29 lb/ft^3; Woodward et al. 2011, Lebow et al. 2013). Canadian researchers have also reported no failures in pentachlorophenol-treated posts after 41 years of exposure (Morris and Ingram 2010).

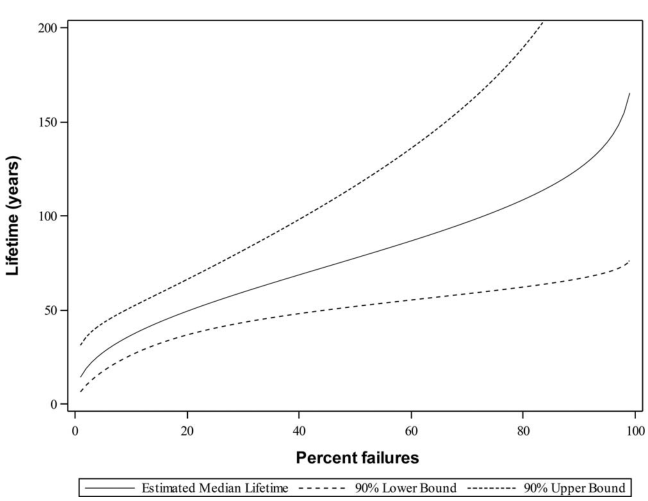

Figure 2.—Approximate 90 percent confidence intervals on estimated lifetime for a given percentile of failures in creosote-treated posts.

Implications for in-service durability of posts, poles, and piles

The results of this 50-year durability evaluation have direct implications for the expected service life of posts, poles, piles, and other round structural members used in contact with the ground. The 100 percent survival rate of the CCA-treated posts is somewhat remarkable considering that a total of 125 posts are represented by the five treatment groups. Based on preservative uptake, 28 (22%) of the posts had retentions below the AWPA ground-contact minimum of 6.4 kg/m^3 (0.4 lb/ft^3). Average CCA retentions by chemical assay were generally below that that required for poles and well below that required for piles. Poles and piles treated with CCA to AWPA standards would be expected to be at least as durable as the posts evaluated in this study. Posts treated with pentachlorophenol have also been highly durable, with no failures observed for the 75 posts installed. The retentions evaluated were close to those standardized for poles but below those standardized for piles or timbers. Poles treated with pentachlorophenol to AWPA standards could be expected to be as durable as the posts in this study, while piles treated to the higher AWPA standard retention would be expected to be more durable.

In general, the preservative treatments evaluated in this study have demonstrated excellent durability considering the severe deterioration hazard at the test site. The expected life of the CCA- and pentachlorophenol-treated posts could not be calculated because of the lack of failures, but these estimates clearly would exceed those calculated for ACA- and creosote-treated posts. The durability of the CCA-treated posts relative to creosote-treated posts is also notable considering that specifiers sometimes express concerns that wood treated with water-based treatments, such as CCA, will not be as durable as wood treated with creosote (Lebow and Wacker 2012).

The application of these test results to in-service treated products has several caveats. The push/pull evaluation method used for the posts did not encompass the wide range of loads applied to in-service posts, poles, or piles, and it may not have detected posts in the early stages of deterioration. In addition, the test posts were not subjected to posttreatment fabrication (e.g., drilling of holes), abrasion, and other forces that can lessen the preservative efficacy for in-service treated products. The posts were also dried and treated under laboratory conditions, and although they were treated to a range of retentions, overall treatment quality may be more uniform than that of in-service commodities.

Conclusions

Posts treated with preservatives similar to those in current commercial use have been highly durable during 50 years of exposure at a test site in southern Mississippi. No failures have occurred in any of the 125 CCA-treated posts or 75 pentachlorophenol-treated posts. Failure occurred in 3 of 25 ACA-treated posts and in 5 of 25 creosote-treated posts. Estimated times to 50 percent failure in the ACA- and creosote-treated posts were calculated as 96 and 78 years, respectively. The estimated time to failure for 50 percent of the CCA- and pentachlorophenol-treated posts could not be calculated because of the lack of failures but likely would be greater than that calculated for ACA- and creosote-treated posts. The durability of the posts is notable because the exposure site presents a severe biodeterioration hazard. The results of this study indicate that posts, poles, and piles treated to standardized retentions with these preservatives may also be highly durable. However, it should be noted that these experimental posts have not been subjected to posttreatment fabrication, mechanical abrasion, or other factors that can lessen the efficacy of preservative treatments for in-service wood products.

Acknowledgment

The authors would like to acknowledge their predecessors at the Forest Products Laboratory, who had the foresight to establish these long-term post durability trials.

Literature Cited

Al-Wazeer, A., B. Harris, and C. Nutakor. 2005. Applying LCCA to bridges. *Public Roads* 69(3). Publication No. FHWA-HRT-05-001. http://www.fhwa.dot.gov/publications/publicroads/05nov/09.cfm. Accessed February 16, 2011.

American Wood Protection Association (AWPA). 2013a. Standard field test for evaluation of wood preservatives to be used in ground contact (UC4A, UC4B, UC4C); stake test. E7-13. *In:* 2013 AWPA Book of Standards. AWPA, Birmingham, Alabama. pp. 431–439.

American Wood Protection Association (AWPA). 2013b. Standard method for the determination of retention of oil-type preservatives from small samples. A6-09. *In:* 2013 AWPA Book of Standards. AWPA, Birmingham, Alabama. pp. 221–223.

American Wood Protection Association (AWPA). 2013c. Standard methods for analysis of oil-borne preservatives. A5-11. *In:* 2013 AWPA Book of Standards. AWPA, Birmingham, Alabama. pp. 206–220.

American Wood Protection Association (AWPA). 2013d. Standard methods for analysis of waterborne preservatives and fire retardant formulations. A2-11. *In:* 2013 AWPA Book of Standards. AWPA, Birmingham, Alabama. pp. 184–196.

American Wood Protection Association (AWPA). 2013e. Standards for solvents and formulations for organic preservative systems. P9-10. *In:* 2013 AWPA Book of Standards. AWPA, Birmingham, Alabama. pp. 122–123.

American Wood Protection Association (AWPA). 2013f. Commodity specifications. D: Poles. *In:* 2013 AWPA Book of Standards. AWPA, Birmingham, Alabama. pp. 45–50.

American Wood Protection Association (AWPA). 2013g. User specification for treated wood. U1-13. *In:* 2013 AWPA Book of Standards. AWPA, Birmingham, Alabama. pp. 5–71.

Best, C. W. and C. C. Coleman. 1982. AWPA Standard M11: An example of its use. *In:* Proceedings of the 77th Annual Meeting of the American Wood-Preservers' Association, April 26–29, 1981, Kissimmee, Florida; American Wood Protection Association, Birmingham, Alabama. pp. 35–40.

Bolin, C. A. and S. T. Smith. 2011. Life cycle assessment of pentachlorophenol-treated wooden utility poles with comparisons to steel and concrete utility poles. *Renewable Sustain. Energy Rev.* 15(5):2475–2486.

Davidson, H. L. 1977. Comparison of wood preservatives in Mississippi Post Study (1977 progress report). FPL-RN-01. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. 17 pp. http://www.fpl.fs.fed.us/documnts/fplrn/fplrn001.pdf.

Freeman, M. H., D. M. Crawford, P. K. Lebow, and J. A. Brient. 2005. A comparison of wood preservatives in posts in southern Mississippi: Results from a half-decade of testing. *In:* Proceedings of the 101st Annual Meeting of the American Wood-Preservers' Association, May 15–17, 2005, New Orleans, Louisiana; American Wood Protection Association, Birmingham, Alabama. pp. 136–143.

Lebow, S. and J. Wacker. 2012. Common questions and concerns from government users of industrial treated wood products. *In:* Proceedings of the 107th Annual Meeting of the American Wood Protection Association, May 15–17, 2011, Fort Lauderdale, Florida; American Wood Protection Association, Birmingham, Alabama. pp. 218–221.

Lebow, S., B. Woodward, G. Kirker, and P. Lebow. 2013. Long-term durability of pressure-treated wood in a severe test site. *Adv. Civ. Eng. Mater.* 2(1):178–188.

Lebow, S. T., B. M. Woodward, and P. K. Lebow. 2014. Documenting the service life of preservative treated wood. *In:* Proceedings of the 108th Annual Meeting of the American Wood Protection Association, April 29–May 2, 2012, Nashville, Tennessee; American Wood Protection Association, Birmingham, Alabama. pp. 166–170.

Mackisack, M. S. and R. H. Stillman. 1996. A cautionary tale about Weibull analysis. *IEEE Trans. Reliab.* 45(2):244–248.

Meeker, W. O. and L. A. Escobar. 1998. Statistical Methods for Reliability Data. John Wiley and Sons, New York. 680 pp.

Morrell, J. J. 2008. Estimated service life of wood poles. Technical Bulletin. North American Wood Pole Council. http://www.woodpoles.org/documents/TechBulletinPoleServiceLife12-08.pdf. Accessed April 5, 2013.

Morrell, J. J. 2012. Performance of wood in posts: An 85 year perspective of the benefits of long term testing. *In:* Proceedings of the 108th Annual Meeting of the American Wood Protection Association, April 29–May 2, 2012, Nashville, Tennessee; American Wood Protection Association, Birmingham, Alabama. pp. 182–186.

Morris, P., J. K Ingram, and R. Stirling. 2012. Durability of Canadian treated wood. *In:* Proceedings of the 108th Annual Meeting of the American Wood Protection Association, April 29–May 2, 2012, Nashville, Tennessee; American Wood Protection Association, Birmingham, Alabama. pp. 171–181.

Morris, P. I. and J. K. Ingram. 2010. Field testing of wood preservatives. XIX: Industrial preservatives. *In:* Proceedings of the 31st Annual Meeting of the Canadian Wood Preservation Association, October 19–20, 2010, Vancouver, British Columbia; Candian Wood Preservation Association, Campbellville, Ontario. pp. 72–78.

NOAA Fisheries. 2009. The use of treated wood products in aquatic environments: Guidelines to West Coast NOAA Fisheries staff for Endangered Species Act and essential fish habitat consultations in the Alaska, northwest and southwest regions. National Oceanic and Atmospheric Administration Fisheries, Southwest Region. Longbeach, California. 58 pp. http://www.westcoast.fisheries.noaa.gov/publications/habitat/treated_wood_guidelines_final_2010.pdf. Accessed July 21, 2010.

Stewart, A. H. 1996. Wood pole life span: What you can expect. *Wood Pole Newsletter* 20:2–5. http://www.woodpoles.org/PDFDocuments/wpnv20.pdf. Accessed April 5, 2013.

URS Corporation. 2011a. Bridge repair/rehabilitation feasibility study for Bridge Street over Mitchell River. Report prepared for the Commonwealth of Massachusetts Department of Transportation. URS Corporation, Boston, Massachusetts. 347 pp. http://www.chatham-ma.gov/public_documents/ChathamMA_Projects/Chatham%20-%20Rehabilitation%20Feasibility%20Report%20Final%2003-10-20.pdf. Accessed May 17, 2011.

URS Corporation. 2011b. Bridge alternatives evaluation and life cycle cost comparison for Bridge Street over Mitchell River. Report prepared for the Commonwealth of Massachusetts Department of Transportation. URS Corporation, Boston, Massachusetts. 42 pp. http://www.chatham-ma.gov/public_documents/ChathamMA_Projects/Alternatives%20Evaluation%20Report.pdf. Accessed May 17, 2011.

US Department of Transportation. 2002. Life-cycle cost analysis primer. US Department of Transportation Federal Highway Administration, Office of Asset Management, Washington, D.C. 24 pp. http://isddc.dot.gov/OLPFiles/FHWA/010621.pdf. Accessed February 16, 2011.

Webb, D., R. Fox, and R. Pfeiffer. 2010. Creosote posts—Final inspection of the 1958 cooperative test after 50 years of exposure as a ground contact preservative. *In:* Proceedings of the 105th Annual Meeting of the American Wood Protection Association, April 19–21, 2009, San Antonio, Texas; American Wood Protection Association, Birmingham, Alabama. pp. 182–187.

Woodward, B. M., C. A. Hatfield, and S. T. Lebow. 2011. Comparison of wood preservatives in stake tests: 2011 progress report. Research Note FPL-RN-02. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. 120 pp. http://www.fpl.fs.fed.us/documnts/fplrn/fpl_rn02.pdf.