United States
Department of
Agriculture

Forest Service

Forest
Products
Laboratory

General
Technical
Report
FPL–GTR–187

Heat-Treatment Options and Heating Times for Ash Firewood

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Abstract

Because of the potential risk associated with moving firewood infested with emerald ash borer, the interstate movement of all hardwood firewood is currently restricted under Federal quarantine. Communities and firewood producers are now faced with decisions on how to treat firewood for interstate commerce. New regulations for heat sterilization of ash firewood require holding a core temperature of 160 °F for 75 min, much higher than the current international heating standard for treating solid wood packaging. The present study evaluated different heat-treatment options for various firewood operations and developed heat-treating schedules and heating time tables. We first conducted laboratory heating experiments using green and air-dried ash firewood and obtained heating time data for different heating schemes. Mathematical models were developed to estimate heating times for heating conditions not tested in the experiment. Heating time tables were developed for a series of heating temperatures and initial wood temperatures. Our field heat-treatment trial in a commercial dry-kiln facility indicated a significant difference in heating times between the laboratory kiln runs and the field kiln run. Although the size of kiln could have contributed to the increase of heating times in the field trial, the type of kiln and heat sources are the main factors that control the heating rate and result in differences in heating times. More field heat-treatment trials at different types of kiln facilities (steam, hot water, and direct fire) should be conducted in the future to calibrate the heating time tables developed through the laboratory experiments.

Keywords: ash firewood, emerald ash borer (EAB), heat treatment, dry heat, wet heat

November 2009

Wang, Xiping; Bergman, Richard; Simpson, William T.; Verrill, Steve; Mace, Terry. 2009. Heat-treatment options and heating times for ash firewood. General Technical Report FPL-GTR-187. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 29 p.

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Acknowledgments

This project was funded in part through a grant awarded by the Wood Education and Resource Center, Northeastern Area State and Private Forestry, Forest Service, U.S. Department of Agriculture (07-DG-114). Materials for laboratory experiments were provided by Green Thumb Farms, Inc. (Prairie du Sac, Wisconsin) and Norske Wood Works II, Inc. (Black Earth, Wisconsin). We especially thank Scott Myers and JoAnn Cruse of USDA Animal and Plant Health Inspection Service (APHIS), Andrea Diss-Torrance of Wisconsin Department of Natural Resources, and Keith Jacobson of Minnesota Department of Natural Resources for providing guidance and assistance to the project. We also thank Green Thumb Farms for participating in the field heat-treatment trial of the study (Prairie du Sac, Wisconsin).

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Conversion Table

English unit	Conversion factor	SI unit
Btu	$1.055\,056 \times 10^3$	joule (J)
inch (in.)	25.4	millimeter (mm)
Temperature increment (°F)	0.556	Temperature increment (°C)
cubic feet (ft^3)	0.0283	cubic meter ($m)^3$
Pound (lb)	453.6	gram (g)

Heat-Treatment Options and Heating Times for Ash Firewood

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Introduction

Emerald ash borer (EAB), *Agrilus planipennis*, is a non-native bark- and wood-infesting insect of Asian origin that poses an enormous threat to North American urban and rural forests. Since its discovery in southeastern Michigan in summer 2002 (Haack and others 2002), EAB has killed millions of ash (*Fraxinus* spp.) trees in Canada and the United States. As of September 2009, the infested area includes two Canadian provinces (Ontario and Quebec) and 13 states (Illinois, Indiana, Kentucky, Maryland, Minnesota, Michigan, Missouri, New York, Ohio, Pennsylvania, Virginia, West Virginia, and Wisconsin) in the United States (Michigan State University 2009). The U.S. Forest Service estimates that if EAB is not contained or eradicated, it has the potential to cost local governments and homeowners approximately $7 billion (present dollars) over the next 25 years to remove and replace dead and dying ash trees (USDA 2008). This scenario would also result in extensive environmental damage and long-term changes in the North American forest structure. To stop further spread of EAB, quarantines are currently in place to prevent infested ash firewood, logs, or nursery trees from being transported and starting new infestations.

Heat sterilization is currently the most practical and environmentally friendly treatment to kill pests in solid wood materials and prevent the transfer of pests between regions and states. Current international regulations for heat sterilization of solid wood packaging materials require a minimal core temperature of 133 °F for 30 min (FAO 2006; CFR 2004). To deal with the potential of EAB moving on firewood, the U.S. Department of Agriculture (USDA) Animal and Plant Health Inspection Service (APHIS) has implemented a new heating standard for treating ash firewood. The new regulations require that the core of the firewood be heated to at least 160 °F for a minimum of 75 min (APHIS 2009). Consequently, the heating schedules developed for heat-treating solid wood packaging materials are not acceptable for treating firewood.

In heat-treating ash firewood, one practical concern is to estimate how long it will take to heat firewood of various forms and sizes to the lethal temperature of 160 °F. The heating time can vary widely depending on a number of factors such as size, wood density, initial moisture content, initial wood temperature, heating temperature, and heating medium. Without reasonable estimates of heating time, sterilization is at best inefficient in terms of time, energy consumption, and equipment usage; and at worst, we risk failure to kill the pest and prevent the spread of EAB or other non-native invasive species.

The goals of our project were to evaluate different heat-treatment options that may suit the needs of various firewood operations and develop heat-treating schedules and heating time tables that will help firewood producers to plan and execute effective heat-treating operations. The specific objectives were the following:

1. Examine different heat-treatment options that meet the new heating standard for EAB and suit the needs of various firewood operations.
2. Quantify the effects of kiln temperature on the time required to heat the center of ash firewood to 160 °F and develop experimental heating time data for different heating schemes.
3. Build mathematical models to estimate heating times for heating conditions that were not tested in the experiment and develop user-friendly heating time tables that cover a range of heating conditions.
4. Examine the applicability of the heating schedules and heating time tables in production-scale heat-treatment operations through a field trial.

Materials and Methods

This project was conducted in two phases. Phase 1 consisted of a series of laboratory heating experiments designed to evaluate a variety of heat-treatment schedules suitable

[a] This project was completed while Dr. Wang was working as a Senior Research Associate at the Natural Resources Research Institute of the University of Minnesota-Duluth.

for commercial firewood operations. Phase 2 was a field heat-treatment trial designed to examine applicability of the heating schedules and heating time tables developed in Phase 1 in a production-scale operation.

Phase 1—Laboratory Experiments

Laboratory experiments were designed to heat-treat green and seasoned ash firewood to meet the heat-treatment standard for EAB (a minimum firewood core temperature of 160 °F for a minimum of 75 min) set by USDA APHIS (2009). The research approach was to obtain experimental data that addressed the most important factors that influence heat sterilization of firewood. These are heating medium, heating temperature, wood density, initial moisture content, and initial wood temperature.

Approximately 23 face cords (980 ft^3) of split, barked ash firewood in 16- to 18-in. lengths were provided by two local firewood producers (a full cord was assumed to equal three face cords, 128 ft^3) (Fig. 1). The laboratory heating experiments were conducted under three heating schemes, two heating schemes for treating green ash firewood and one for treating seasoned ash firewood as shown.

1. Dry-heat schedules for heat-treating green ash firewood with moisture reduction
   - Dry-bulb temperature: 160, 170, 180, 200, 240, and 280 °F
   - Wet-bulb temperature: allow to seek its own level (no water or steam spray)
2. Wet-heat schedules for heat-treating green ash firewood without moisture reduction
   - Dry-bulb temperature: 160, 170, and 180 °F
   - Wet-bulb depression: 0 and 10 °F (with water or steam spray)
3. Dry-heat schedule for heat-treating seasoned (< 20% MC) ash firewood
   - Dry-bulb temperature: 160, 170, and 180 °F
   - Wet-bulb temperature: allow to seek its own level (no water or steam spray)

A total of 15 experimental kiln runs were conducted in the laboratory to obtain necessary heating data, including six runs for scheme 1, six runs for scheme 2, and three runs for scheme 3. Each kiln run contained 1.5 face cords of ash firewood, including various forms and sizes that are normally produced by a firewood splitting machine. Thirty of the largest firewood pieces were selected to monitor temperature for each kiln run (Fig. 2). Prior to conducting the experimental runs, these 30 firewood samples were randomly divided into three groups of 10 pieces that were conditioned to three different initial temperatures: 1) freezer temperature (0 °F chamber); 2) cold temperature (34 °F chamber); and 3) room temperature (70 °F). The firewood pieces of each run were randomly placed within a 4- by 4- by 8-ft steel basket to simulate common industry practice, with the monitored samples buried within the pile of firewood (Fig. 3).

Figure 1. Green ash firewood provided by local firewood producers.

Figure 2. Largest firewood samples selected for temperature monitoring.

Figure 3. Basket filled with firewood with temperature-monitoring samples buried within the pile.

Figure 4. A thermocouple inserted into the center of a piece of firewood at the middle section.

The experimental runs were conducted in an 800-board-foot research dry kiln at the Forest Products Laboratory in Madison, Wisconsin. The kiln has the capacity to reach a kiln temperature of 300 °F and create various heating conditions that might be in the practical range of field practice. The core temperatures of the 30 firewood samples monitored per run were measured with thermocouples inserted to the geometric center of each piece of firewood. Figure 4 shows a thermocouple wire inserted into a hole and the hole plugged with sealant and a round toothpick to prevent ambient kiln air from influencing the thermocouple reading at the center. The core temperatures of the firewood samples were monitored using a Keithley Model 2700 Multimeter/Data Acquisition System (Keithley Instruments, Inc., Cleveland, Ohio) and written to computer files at 1-min intervals. The data logging system was set to start recording temperature data once the kiln door was closed and the kiln started running. For test runs under heating scheme 1, moisture content (MC) changes were also monitored by periodically weighing four kiln samples.

Phase II—Production Trial

Three heat-treatment trial runs were conducted in a commercial kiln at Green Thumb Farms, Inc., a firewood producer in Prairie du Sac, Wisconsin. The kiln facility at Green Thumb Farms includes a hot water boiler (fueled with the facility's waste wood) and a dry kiln with a capacity of holding approximately 14 cords of firewood (42 face cords, 1,792 ft^3). Because of insufficient heat capacity, poor air circulation, and lack of insulation on hot water pipes, the kiln temperature at this facility was limited to 160 °F in winter and 170 °F in summer. Before the heat-treatment trial, improvements to the kiln and heating system were made to meet the basic temperature requirements of low-temperature heating schedules.

- Added extra fin pipes inside the kiln to increase heating area
- Added baffles to improve air circulation inside the kiln
- Insulated the hot water pipes between the hot water boiler and the kiln

Three field heat-treatment trial runs were conducted on April 22–27, August 4–8, and August 19–21, 2008. Figure 5 shows the layout of the kiln and locations of the firewood samples with thermocouples inserted to monitor internal wood temperature. In each trial run, a total of 27 baskets was used. Baskets were arranged in three levels (bottom, middle, and upper), with nine baskets on each level. We monitored the core temperatures of six to nine firewood samples during trial runs by placing one sample into one of the baskets in the bottom level where the air temperature is usually lower than that of higher levels.

Green Thumb Farms has been kiln-drying firewood for interstate commerce for several years. Firewood loads are typically kiln-dried weekly throughout the year. A dry-heat schedule that heat-treats the firewood loads with moisture reduction would best fit the production needs of the facility. Because the heat energy is provided through a hot water boiler (fueled with wood waste), the kiln has limited heating capacity in terms of British thermal units (Btu) and kiln temperature. After the kiln improvements were made, we expected that the kiln would be capable of reaching 170 °F in winter and 180 °F in summer. The field trial at this facility would allow us to test the dry-heat schedules in a low temperature range at 170–180 °F and verify the heating times developed from the laboratory experiments.

Results and Discussion

Experimental heating times for ash firewood were determined on the basis of recorded core temperature history for each kiln run. This heating time included an initial heating period in each test run but did not include the 75-min holding period. The heating time analysis in the present study is primarily focused on the temperature requirement of the current heat-treatment standard for firewood: 160 °F. However, considering that future development may identify new temperature–time regimes with lower temperatures but longer heating periods, we also derived heating times to a center temperature of 150 °F from the same temperature history data.

Heat-Treating Green Firewood with Moisture Reduction (Dry-Heat Schedule)

This heat-treating strategy integrates the heat-treatment procedures with a kiln-drying process and is considered as a primary option by many firewood producers who have dry-kiln facilities. The heating medium used is typically dry heat (no additional moisture added). The firewood pieces are first heated to the target core temperature of 160 °F and held for at least 75 min (heat-treatment stage). After the

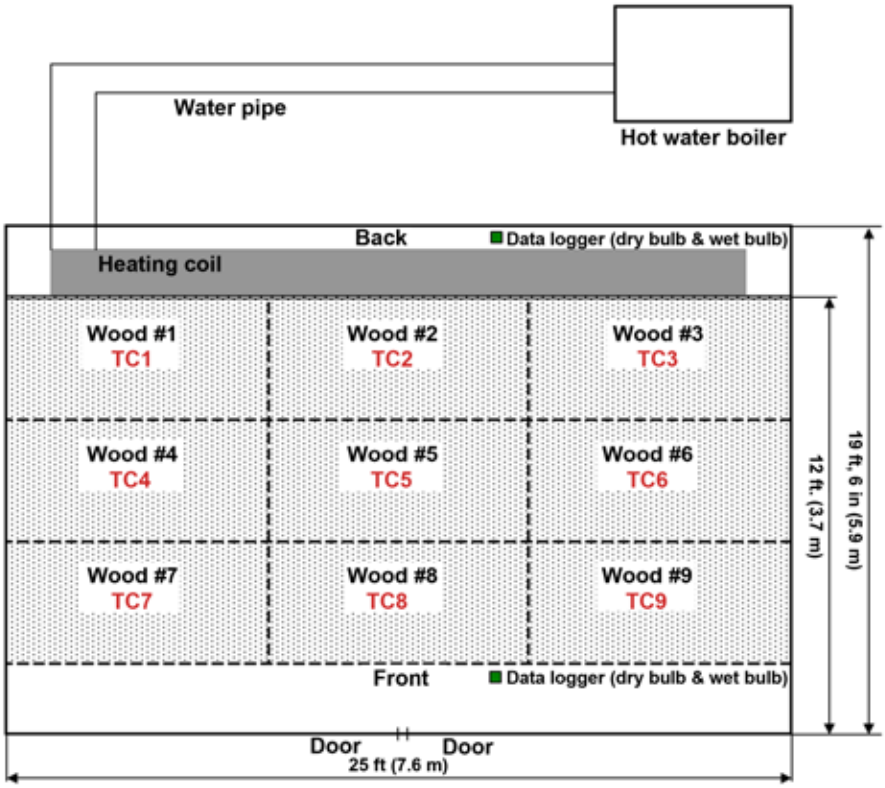

Figure 5. Kiln layout and locations of firewood samples and thermocouples for temperature monitoring in the field heat-treatment trial.

heating standard is met, the firewood loads are continuously heated and kiln dried until the moisture content of the firewood reaches 20% or below (kiln-drying stage). The heating capacity of dry-kiln facilities for firewood businesses varies widely. Maximum kiln temperature can range from below 160 °F to over 280 °F, depending on the types of kiln and energy sources used. One major objective of our study was to quantify the effects of kiln temperature on the time required to heat the center of ash firewood to the target temperature and develop heating time tables that cover a range of heating conditions that might be used in field operations. In our laboratory heating experiments, the kiln runs for heating scheme 1 were set to a series of dry-bulb temperatures (nominal 160, 170, 180, 200, 240, and 280 °F). No water or steam spray was introduced, and wet-bulb temperature was allowed to seek its own value under each heating condition.

Experimental Heating Times

Tables 1 and 2 summarize the kiln conditions and measured heating times to the core temperature of 160 and 150 °F, respectively. The heating time to a core temperature of 160 °F (current heating standard) for ash firewood ranged from a few hours at kiln temperatures of 240 and 280 °F to over 10 h at a kiln temperature of 170 °F. We found that initial temperature of firewood had a practical effect on heating times when kiln temperature was 200 °F and below. As expected, the lower the initial wood temperature, the longer the heating time. This implies that heat-treating operations in winter should take into account initial firewood temperature and plan for longer heating times than in warmer seasons.

Conversely, our results showed that initial wood temperature had little effect on heating time when kiln temperature was 240 °F and above. This result is likely limited to our experimental cases where only two groups of firewood samples (10 pieces for each group) were conditioned to cold 34–36 °F and freezing 11–27 °F temperatures. The remaining pieces of firewood in the basket exhibited the same temperature as outside environments where firewood was stored. Therefore, a longer heat-up time would be expected for a kiln load of frozen firewood compared with just a few pieces. We recommend that the effect of initial temperature should be properly considered in heat-treatment operations, even when kiln temperature is 240 °F and above.

The kiln run with 160 °F dry-bulb temperature failed to meet the current heat-treatment standard (160 °F core temperature). This was expected, as we learned from a previous study (Simpson and others 2005) that wood core temperature is always below the kiln temperature when the heating medium is not saturated steam. This experimental run demonstrated that facilities unable to produce a kiln temperature higher than 160 °F will not be able to meet the current EAB heat-treatment standard.

Table 1—Summary of experimental heating times to a core temperature of 160 °F[a] for green ash firewood with dry-heat schedules

Kiln temperature setting (°F)	Actual kiln temperature (°F)		Initial temperature of firewood (°F)	Measured heating times (min)		
	Dry bulb	Wet bulb		Average	Minimum	Maximum
170	167	116	13	471	370	672
			36	411	290	635
			69	396	333	484
180	176	120	27	251	199	325
			43	232	199	271
			69	198	176	257
200	195	128	14	198	164	231
			34	161	143	208
			63	144	94	173
240	234	155	11	133	92	185
			34	126	109	157
			70	118	89	138
280	272	160	16	142	103	185
			36	139	104	159
			64	129	83	146

[a]Current regulations from APHIS (2009).

Table 2—Summary of experimental heating times to a core temperature of 150 °F for green ash firewood with dry-heat schedules

Kiln temperature setting (°F)	Actual kiln temperature (°F)		Initial temperature of firewood (°F)	Measured heating times (min)		
	Dry bulb	Wet bulb		Average	Minimum	Maximum
170	167	116	13	291	229	375
			36	276	204	352
			69	258	233	291
180	176	120	27	187	149	251
			43	170	149	199
			69	145	132	186
200	195	128	14	165	135	198
			34	132	117	172
			63	118	73	144
240	234	155	11	110	74	156
			34	101	87	122
			70	93	66	93
280	272	160	16	124	86	169
			36	122	90	144
			64	111	71	130

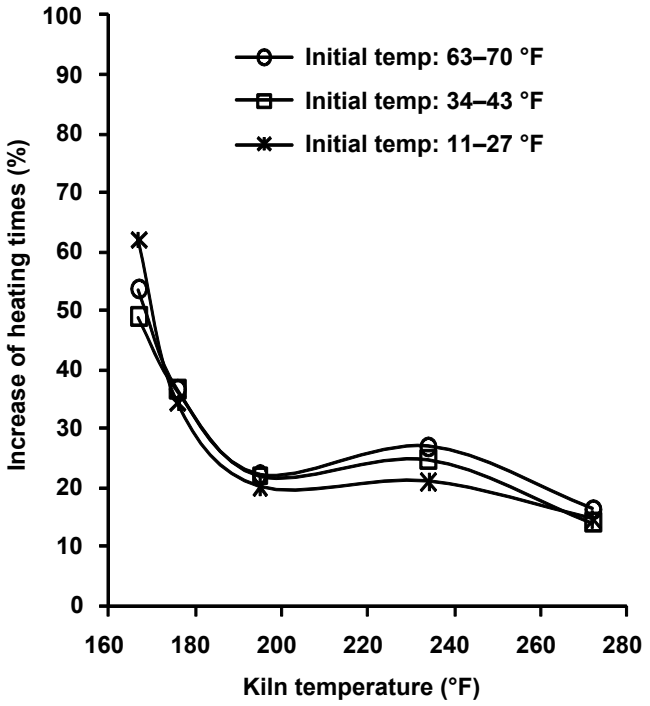

Figure 6. Percentage increase of heating times as the core temperature changes from 150 to 160 °F.

The results of our laboratory experiments also indicated that under the same heating conditions, the heating time to a core temperature of 160 °F was substantially longer than the time to heat to a core temperature of 150 °F. As an example, Figure 6 shows the percentage increase in heating time at various heating conditions as the target core temperature increases from 150 °F to 160 °F. Note that heating time increase was more prominent when the kiln temperature was below 200 °F. This finding supports the incentive of developing a more efficient time–temperature heating regime that has a lower core temperature and a longer holding period.

Mathematical Model for Estimating Heating Times

Heating time is affected by both heating conditions and physical properties of firewood. No single experiment of practical scope would cover them all. Therefore, we developed mathematical models to predict heating times for the heating conditions that were not tested in the laboratory experiments. Several empirical models were tested, and the following four-parameter regression model provided the best fit to the experimental data:

$$\ln(t) = a_0 + a_1(1/T) + a_2 \ln(T_0) + a_3 \ln(W/l)$$

where

t is heating time,
T kiln temperature (dry-bulb) (°F),
T_0 initial wood temperature (°F),
W weight of firewood (g), and
l length of firewood (in.).

The geometrical form and size of typical firewood is not uniform. We eliminated the size factor in the experiments by only selecting the largest pieces of firewood in each experimental run. The weight per unit length (W/l) of the firewood samples was included in the model and considered as a parameter that accounts for tree species, density, and initial moisture content differences.

Heating data from the 160 °F kiln run was excluded from regression analysis because the firewood failed to reach the target core temperature of 160 °F. In addition, four extreme outliers, including one low outlier and three high outliers, were removed to ensure that the model would be fit to the main body of the data. The low outlier was the result of a thermocouple being pulled out of a firewood sample during kiln loading, causing an extremely short heating time. The three high outliers were from the kiln run with an actual average kiln temperature of 167 °F where the three samples were likely located in the cold side of the kiln with an air temperature of 163 °F. This low temperature was not a representative heating condition for this particular run; therefore, we removed these three high outliers from the main body of the experimental data.

Separate regressions were developed for two different target core temperatures: 160 and 150 °F. The parameter estimates and the associated *p*-values are provided in Table 3. The regression model yielded a reasonably good correlation between predicted heating time and experimental heating data. For the multiple regression model of the time to a 160 °F core temperature, the root mean squared error (after predictions have been transformed back into the original

Table 3—Parameter estimates and *p*-values for the multiple regression model

	Model for 71 °C (160 °F) core temperature		Model for 65 °C (150 °F) core temperature	
Coefficient	Estimate	*p*-value	Estimate	*p*-value
a_0	0.534	0.4790	0.703	0.2837
a_1	441.7	0.0001	339.6	0.0001
a_2	–0.108	0.0001	–0.110	0.0001
a_3	0.555	0.0001	0.571	0.0001

Table 4—Summary of experimental heating times to a core temperature of 160 °F[a] for green ash firewood with wet-heat schedules

Nominal kiln temperature (°F)		Initial wood temperature (°F)	Heating time (min)		
Dry bulb	Wet-bulb depression		Average	Minimum	Maximum
160	0	76	200	149	239
160	10	74	229	165	273
170	0	64	152	114	196
170	10	53	205	160	241
180	0	56	151	119	189
180	10	60	159	124	197

[a]Current regulations from APHIS (2009).

Table 5—Summary of experimental heating times to a core temperature of 150 °F for green ash firewood with wet-heat schedules

Nominal kiln temperature (°F)		Initial wood temperature (°F)	Heating time (min)		
Dry bulb	Wet-bulb depression		Average	Minimum	Maximum
160	0	76	133	96	173
160	10	74	162	121	194
170	0	64	119	91	158
170	10	53	157	122	194
180	0	56	124	97	158
180	10	60	128	100	163

non-log space) is 69.4 min. The adjusted R^2 in the log space is 0.694. The correlation between the predicted and observed values in the original space is 0.835. Two observations out of the 146 exceeded the corresponding 99% confidence bound on a new observation. For the model 150 °F core temperature, the root mean squared error (after predictions have been transformed back into the original non-log space) is 36.6 min. The adjusted R^2 in the log space is 0.652. The correlation between the predicted and observed values in the original space is 0.840. No observations out of the 146 exceeded the corresponding 99% confidence bound on a new observation.

Heating Time Tables

Multiple regression models were used to predict heating times to core temperatures of both 160 and 150 °F for a series of kiln temperatures, initial wood temperatures, and weight per unit length. The heating time tables developed are shown in Appendices A and B. The tables cover initial wood temperature from 10 to 80 °F, representing ambient temperatures for different times of the year.

The heating times calculated based on the multiple regression models are average times and provide a general estimate of the time required to heat the center of firewood to the target temperature. In any loads of firewood, the average time does not ensure that all pieces will achieve the target temperature, as we observed considerable variation in heating times in these experiments. Therefore, to ensure that the heat-treatment target temperature will be attained during the kiln run, the upper 99% statistical confidence bound for the heating times was calculated based on the equations provided in Appendix C, and the values are provided in Appendices A and B along with the estimated average heating times. Appendix D provides a temperature conversion table.

Heat-Treating Green Firewood without Moisture Reduction (Wet-Heat Schedules)

This heating strategy applies to situations where firewood only needs to be heat-treated to meet the Federal regulations and no drying is required. Heating with wet heat (no or low wet-bulb depression) is the most efficient way to accomplish the heat-treatment goal in this scenario, and it yields much shorter heating times than heating with dry heat.

Tables 4 and 5 show experimental heating times for green ash firewood under several different wet-heat conditions, which were a combination of three kiln temperatures at 160, 170, and 180 °F and two wet-bulb depressions at 0 and 10 °F. The heating times to a core temperature of 160 °F were generally in the range of 2 to 4 h in a fully saturated heating medium with a kiln temperature of 160 to 180 °F. Heating time increased significantly as wet-bulb depression increased from 0 to 10 °F ($p \leq 0.012$). As an example, Figure 7 shows the effect of heating medium on average heating times to core temperatures of 160 and 150 °F for

Table 6—Summary of experimental heating times to a core temperature of 160 °F [a] for seasoned ash firewood with dry-heat schedules[a]

Kiln temperature setting (°F)	Actual kiln temperature (°F)		Initial temperature of firewood (°F)	Measured heating times (min)		
	Dry bulb	Wet bulb		Average	Minimum	Maximum
160	157	110	22 42 66	N/A	N/A	N/A
170	167	97	68	223	128	290
180	176	100	64	169	100	218

[a]Current regulations from APHIS (2009).

Table 7—Summary of experimental heating times to a core temperature of 150 °F for seasoned ash firewood with dry-heat schedules[a]

Kiln temperature setting (°F)	Actual kiln temperature (°F)		Initial temperature of firewood (°F)	Measured heating times (min)		
	Dry bulb	Wet bulb		Average	Minimum	Maximum
160	157	110	22	269	176	336
			42	237	143	307
			66	249	189	323
170	167	97	68	151	89	198
180	176	100	64	130	78	168

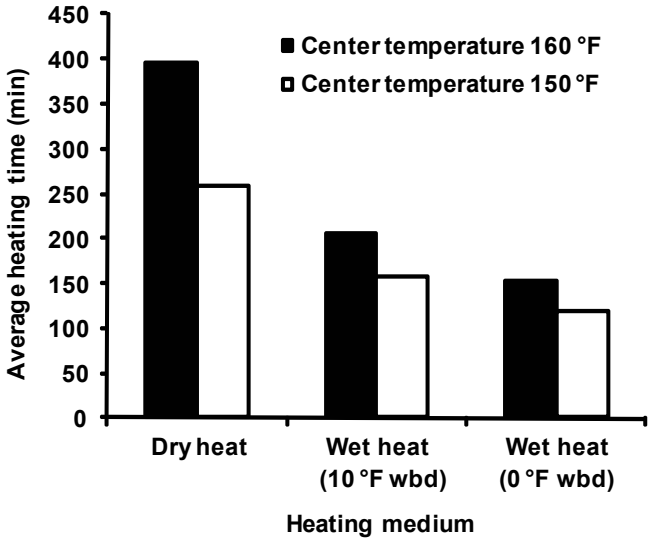

Figure 7. Average heating times for green ash firewood with dry heat and wet heat schedules (dry-bulb temperature of heating medium: 170 °F. Wbd is wet-bulb depression).

green ash firewood in a 170 °F kiln temperature. Note that under similar initial wood temperature conditions, the heating times for wet-heat schedules at 0 and 10 °F wet-bulb depression were significantly lower than the heating times for a dry-heat schedule ($p < 0.001$), and the heating medium with 0 °F wet-bulb depression resulted in the shortest heating time.

Heat-Treating Seasoned Firewood (Dry-Heat Schedules)

Another scenario for commercial firewood producers is heat-treatment of firewood after it has been air-dried. This procedure would only be used to meet the Federal regulations in order to freely move firewood from EAB quarantine areas.

Although both dry-heat and wet-heat schedules can be used to heat-treat seasoned firewood, dry-heat schedules are more likely to be used, as firewood producers who air-dry firewood typically do not have a traditional steam kiln.

The experimental heating times for seasoned firewood with dry-heat schedules are shown in Tables 6 and 7. The comparison of heating times between green and seasoned firewood is illustrated in Figure 8. The results indicated that the heating time for seasoned firewood is significantly less than that for green firewood ($p \leq 0.009$). In the case of 170 °F kiln runs, it took about 2 to 4.8 h to heat the seasoned ash firewood to a core temperature of 160 °F, compared with 5.6 to 8 h for green ash firewood.

Field Heat-Treatment Trial

The temperature histories (kiln temperatures and core temperatures of firewood samples) of the three field heat-treatment trial runs are shown in Figures 9 to 11. The first two trials failed to meet the current EAB heat-treatment standard of 160 °F because of two primary reasons: 1) several water

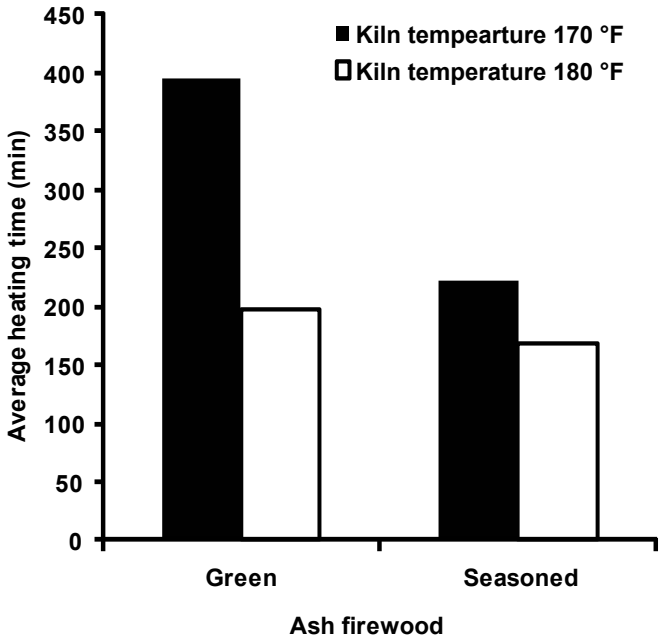

Figure 8. Average heating times to a core temperature of 160 °F for green and seasoned ash firewood.

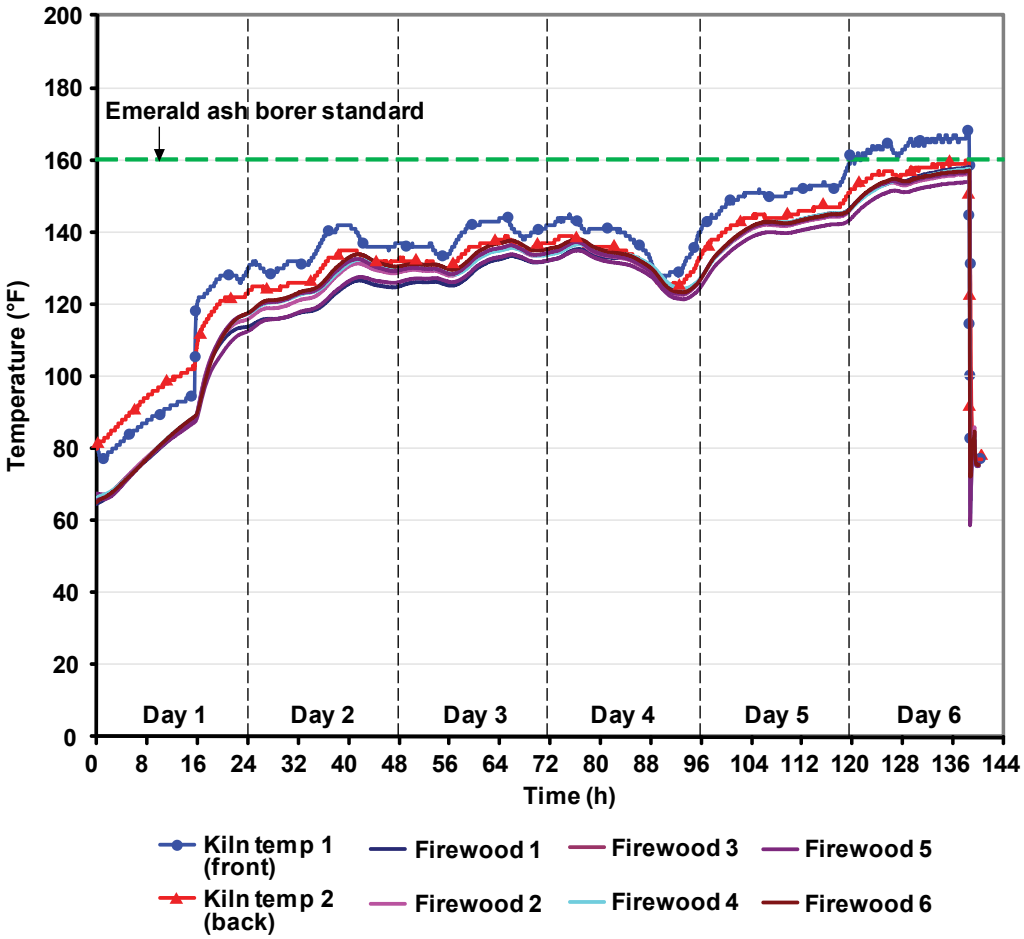

Figure 9. Temperature record of field heat-treatment trial run #1 conducted on April 22–27, 2008.

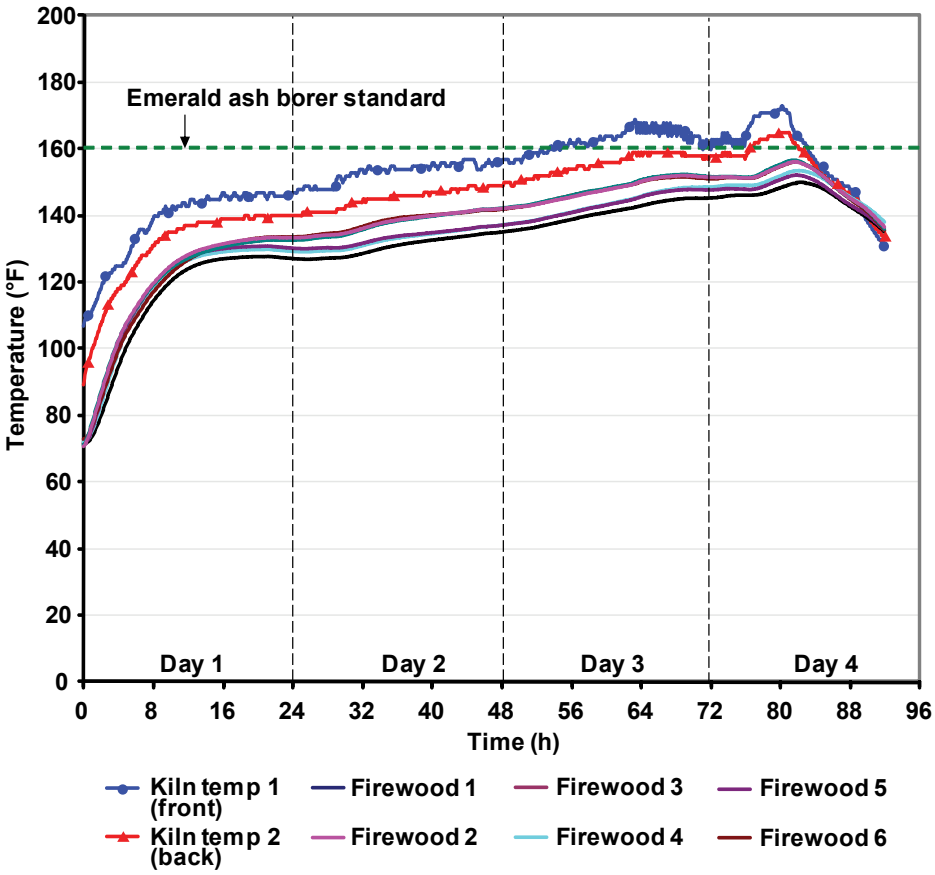

Figure 10. Temperature record of field heat-treatment trial run #2 conducted on August 4–7, 2008.

pumps failed during the heating process; 2) the vents were not closed in the initial heating stage, causing the kiln to lose heat. We also found through these two trials that the flow rate of the original water pumps was too low to bring sufficient heat into the kiln. Before starting the third trial run, Green Thumb Farms replaced all four original pumps with new pumps that have a higher flow rate. The following procedures were also implemented in the third trial to help raise the kiln temperature: 1) keep the vents closed to maintain a high relative humidity within the kiln in the heat-treatment stage; 2) open the vents to release moisture after the heat-treatment requirement of 160 °F for at least 75 min has been met.

The recorded temperature data showed that the third trial run passed heat-treatment requirements. The dry-bulb temperature reached 174 °F in the backside of the kiln (lower temperature spot). Heating time to the core temperature of 160 and 150 °F for green ash firewood in this field trial ranged from 13.2 to 15.3 h and 10.1 to 11.8 h, respectively. Average heating time for the field trial increased significantly compared with that observed in laboratory experiment with a 170 °F dry-heat schedule. This indicates that the type of kiln and energy source have a major effect on actual heating times in field heat-treating operations. Hot water systems generally have a lower heating capacity compared with a traditional steam kiln, which results in lower heating rates and longer heating times. Another contributing factor is the scale of the kiln and the kiln-load factor. The dry kiln at Green Thumb Farms holds 27 baskets of firewood, and the laboratory kiln used in the experimental phase of this study holds only one basket of firewood. Effect of kiln size on heating time is another important consideration for field heat-treatment operations.

Summary

In this project, we examined three different heat-treatment options that are applicable to a variety of commercial firewood operations. Laboratory heating experiments demonstrated the importance of kiln temperature and kiln humidity in meeting the new heat-treatment standard to kill EAB. The current primary heat-treatment mode for many firewood producers is to use dry-heat schedules to heat-treat and kiln-dry green firewood in one operation. Based on experimental heating data, we developed mathematical models to predict average heating times to a core temperature of both 160 and 150 °F for green ash firewood under various heating conditions. We also developed heating time tables for a series of heating temperatures and different initial wood

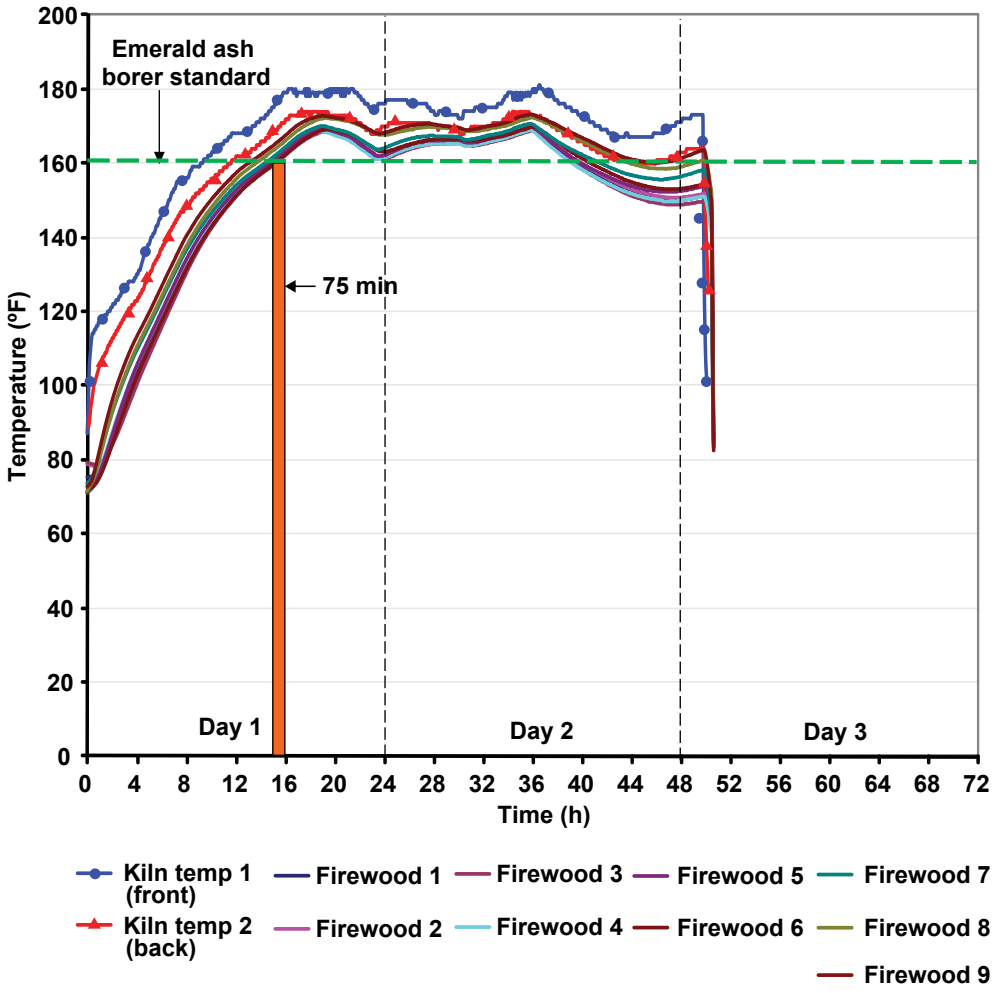

Figure 11. Temperature record of field heat-treatment trial run #3 conducted on August 19–21, 2008.

temperatures. The tables provide both average heating time and the corresponding 99% upper confidence bound. The prediction models and heating time tables were developed on the basis of laboratory experiments in a small-scale dry kiln (approximately 1.5 face cord capacity) with well controlled heating conditions and have not been calibrated to field operations. Our limited field heat-treatment trials indicated a significant difference in heating times between laboratory kiln runs and field kiln run. Although the size of the kiln could have contributed to increase of heating times in field trials, the type of kiln and heat source (hot water system) are the main factors that control the heating rate and result in differences in heating times. More field heat-treatment trials at different types of kiln facilities (steam, hot water, and direct fire) should be conducted in the future to better calibrate the heating time tables developed in this project.

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Appendix A—Predicted Heating Times to a Core Temperature of 160 °F for Green Ash Firewood

See Appendix D for temperature conversions.

Kiln temperature (°F)	Initial wood temperature (°F)	Unit weight length (g/in.)	Heating time (min)	
			Predicted	99% upper confidence bound
170	10	120	254.4	480.8
170	10	160	298.4	554.9
170	10	200	337.7	626.1
170	10	240	373.6	695.3
170	10	280	407	763.1
170	30	120	225.9	422.9
170	30	160	264.9	488.6
170	30	200	299.9	551.9
170	30	240	331.8	613.6
170	30	280	361.4	674
170	50	120	213.7	399.8
170	50	160	250.7	462.3
170	50	200	283.7	522.5
170	50	240	313.9	581.1
170	50	280	342	638.6
170	65	120	207.7	388.9
170	65	160	243.7	449.8
170	65	200	275.8	508.5
170	65	240	305.2	565.7
170	65	280	332.4	621.7
170	80	120	203.1	380.6
170	80	160	238.3	440.4
170	80	200	269.7	497.9
170	80	240	298.4	554
170	80	280	325	608.9
180	10	120	220.2	415.5
180	10	160	258.3	479.5
180	10	200	292.3	541
180	10	240	323.4	600.8
180	10	280	352.3	659.4
180	30	120	195.5	365.5
180	30	160	229.3	422.3
180	30	200	259.6	477
180	30	240	287.2	530.3
180	30	280	312.8	582.5
180	50	120	185	345.6
180	50	160	217	399.7
180	50	200	245.6	451.7
180	50	240	271.8	502.4
180	50	280	296	552

Kiln temperature (°F)	Initial wood temperature (°F)	Unit weight length (g/in.)	Heating time (min)	
			Predicted	99% upper confidence bound
180	65	120	179.8	336.2
180	65	160	210.9	388.9
180	65	200	238.7	439.6
180	65	240	264.1	489
180	65	280	287.7	537.5
180	80	120	175.8	329
180	80	160	206.3	380.7
180	80	200	233.4	430.5
180	80	240	258.3	479
180	80	280	281.3	526.5
190	10	120	193.5	364.8
190	10	160	227	420.9
190	10	200	256.9	474.9
190	10	240	284.2	527.5
190	10	280	309.6	578.9
190	30	120	171.8	320.9
190	30	160	201.6	370.9
190	30	200	228.1	418.9
190	30	240	252.4	465.7
190	30	280	274.9	511.6
190	50	120	162.6	303.6
190	50	160	190.7	351
190	50	200	215.9	396.7
190	50	240	238.8	441.2
190	50	280	260.1	484.8
190	65	120	158	295.3
190	65	160	185.4	341.5
190	65	200	209.8	386.1
190	65	240	232.1	429.5
190	65	280	252.9	472.1
190	80	120	154.5	289
190	80	160	181.3	334.4
190	80	200	205.2	378.1
190	80	240	227	420.7
190	80	280	247.3	462.4
200	10	120	172.3	324.6
200	10	160	202.1	374.5
200	10	200	228.7	422.6
200	10	240	253	469.3
200	10	280	275.6	515.1
200	30	120	153	285.6
200	30	160	179.4	330.1
200	30	200	203.1	372.8
200	30	240	224.7	414.5
200	30	280	244.8	455.3

Kiln temperature (°F)	Initial wood temperature (°F)	Unit weight length (g/in.)	Heating time (min)	
			Predicted	99% upper confidence bound
200	50	120	144.7	270.2
200	50	160	169.8	312.4
200	50	200	192.2	353.1
200	50	240	212.6	392.7
200	50	280	231.6	431.5
200	65	120	140.7	262.8
200	65	160	165	304
200	65	200	186.8	343.7
200	65	240	206.7	382.4
200	65	280	225.1	420.2
200	80	120	137.6	257.3
200	80	160	161.4	297.7
200	80	200	182.6	336.6
200	80	240	202.1	374.5
200	80	280	220.1	411.7
210	10	120	155.1	292.1
210	10	160	181.9	337.1
210	10	200	205.9	380.3
210	10	240	227.8	422.4
210	10	280	248.1	463.6
210	30	120	137.7	257.1
210	30	160	161.5	297.1
210	30	200	182.8	335.6
210	30	240	202.3	373.1
210	30	280	220.3	409.9
210	50	120	130.3	243.3
210	50	160	152.8	281.3
210	50	200	173	317.9
210	50	240	191.4	353.6
210	50	280	208.5	388.5
210	65	120	126.7	236.6
210	65	160	148.6	273.7
210	65	200	168.1	309.5
210	65	240	186	344.3
210	65	280	202.7	378.4
210	80	120	123.8	231.6
210	80	160	145.3	268
210	80	200	164.4	303.1
210	80	240	181.9	337.2
210	80	280	198.2	370.7
220	10	120	140.9	265.5
220	10	160	165.3	306.4
220	10	200	187.1	345.7
220	10	240	207	384
220	10	280	225.5	421.4

Kiln temperature (°F)	Initial wood temperature (°F)	Unit weight length (g/in.)	Heating time (min)	
			Predicted	99% upper confidence bound
220	30	120	125.1	233.8
220	30	160	146.8	270.1
220	30	200	166.1	305.1
220	30	240	183.8	339.2
220	30	280	200.2	372.6
220	50	120	118.4	221.2
220	50	160	138.9	255.7
220	50	200	157.2	289
220	50	240	173.9	321.5
220	50	280	189.5	353.3
220	65	120	115.1	215.2
220	65	160	135	248.9
220	65	200	152.8	281.4
220	65	240	169.1	313
220	65	280	184.2	344
220	80	120	112.5	210.6
220	80	160	132	243.7
220	80	200	149.4	275.6
220	80	240	165.3	306.6
220	80	280	180.1	337
230	10	120	129.1	243.4
230	10	160	151.5	280.9
230	10	200	171.5	316.9
230	10	240	189.7	352
230	10	280	206.6	386.3
230	30	120	114.7	214.3
230	30	160	134.5	247.7
230	30	200	152.3	279.8
230	30	240	168.5	311
230	30	280	183.5	341.7
230	50	120	108.5	202.8
230	50	160	127.3	234.5
230	50	200	144.1	265
230	50	240	159.4	294.8
230	50	280	173.6	323.9
230	65	120	105.5	197.3
230	65	160	123.7	228.2
230	65	200	140	258
230	65	240	154.9	287
230	65	280	168.8	315.5
230	80	120	103.1	193.1
230	80	160	121	223.5
230	80	200	136.9	252.7
230	80	240	151.5	281.2
230	80	280	165	309.1

Kiln temperature (°F)	Initial wood temperature (°F)	Unit weight length (g/in.)	Heating time (min)	
			Predicted	99% upper confidence bound
240	10	120	119.2	224.8
240	10	160	139.8	259.4
240	10	200	158.3	292.7
240	10	240	175.1	325.1
240	10	280	190.8	356.8
240	30	120	105.9	198
240	30	160	124.2	228.8
240	30	200	140.5	258.4
240	30	240	155.5	287.3
240	30	280	169.4	315.6
240	50	120	100.2	187.3
240	50	160	117.5	216.6
240	50	200	133	244.8
240	50	240	147.1	272.3
240	50	280	160.3	299.2
240	65	120	97.4	182.3
240	65	160	114.2	210.9
240	65	200	129.3	238.4
240	65	240	143	265.2
240	65	280	155.8	291.4
240	80	120	95.2	178.4
240	80	160	111.7	206.5
240	80	200	126.4	233.5
240	80	240	139.9	259.8
240	80	280	152.3	285.5
250	10	120	110.8	209
250	10	160	129.9	241.2
250	10	200	147	272.1
250	10	240	162.7	302.2
250	10	280	177.2	331.7
250	30	120	98.4	184.1
250	30	160	115.4	212.7
250	30	200	130.6	240.3
250	30	240	144.5	267.1
250	30	280	157.4	293.4
250	50	120	93.1	174.2
250	50	160	109.2	201.4
250	50	200	123.6	227.7
250	50	240	136.7	253.2
250	50	280	148.9	278.2
250	65	120	90.5	169.5
250	65	160	106.1	196.1
250	65	200	120.1	221.7
250	65	240	132.9	246.6
250	65	280	144.7	271

Kiln temperature (°F)	Initial wood temperature (°F)	Unit weight length (g/in.)	Heating time (min)	
			Predicted	99% upper confidence bound
250	80	120	88.5	165.9
250	80	160	103.8	192
250	80	200	117.4	217.1
250	80	240	129.9	241.6
250	80	280	141.5	265.5
260	10	120	103.5	195.4
260	10	160	121.4	225.5
260	10	200	137.4	254.4
260	10	240	152	282.6
260	10	280	165.6	310.1
260	30	120	91.9	172.1
260	30	160	107.8	198.9
260	30	200	122	224.7
260	30	240	135	249.8
260	30	280	147	274.4
260	50	120	87	162.9
260	50	160	102	188.4
260	50	200	115.4	212.9
260	50	240	127.7	236.8
260	50	280	139.1	260.2
260	65	120	84.5	158.5
260	65	160	99.1	183.4
260	65	200	112.2	207.3
260	65	240	124.2	230.6
260	65	280	135.2	253.4
260	80	120	82.6	155.2
260	80	160	96.9	179.6
260	80	200	109.7	203
260	80	240	121.4	225.9
260	80	280	132.2	248.3
270	10	120	97.2	183.6
270	10	160	114	211.9
270	10	200	129	239.1
270	10	240	142.7	265.6
270	10	280	155.5	291.5
270	30	120	86.3	161.8
270	30	160	101.2	187
270	30	200	114.6	211.2
270	30	240	126.7	234.8
270	30	280	138.1	257.9
270	50	120	81.6	153.1
270	50	160	95.8	177.1
270	50	200	108.4	200.1
270	50	240	119.9	222.6
270	50	280	130.6	244.6

Kiln temperature (°F)	Initial wood temperature (°F)	Unit weight length (g/in.)	Heating time (min)	
			Predicted	99% upper confidence bound
270	65	120	79.4	149
270	65	160	93.1	172.4
270	65	200	105.4	194.9
270	65	240	116.6	216.8
270	65	280	127	238.2
270	80	120	77.6	145.8
270	80	160	91	168.8
270	80	200	103	190.9
270	80	240	114	212.4
270	80	280	124.2	233.4

Appendix B—Predicted Heating Times to a Core Temperature of 150 °F for Green Ash Firewood.

See Appendix D for temperature conversions.

Kiln temperature (°F)	Initial wood temperature (°F)	Unit weight length (g/in.)	Heating time (min)	
			Predicted	99% upper confidence bound
170	10	120	177.6	308.9
170	10	160	209.3	358.9
170	10	200	237.8	406.5
170	10	240	263.8	452.5
170	10	280	288.1	497.4
170	30	120	157.5	271.5
170	30	160	185.6	315.8
170	30	200	210.8	358.1
170	30	240	233.9	398.9
170	30	280	255.4	438.8
170	50	120	148.9	256.5
170	50	160	175.4	298.6
170	50	200	199.3	338.7
170	50	240	221.1	377.5
170	50	280	241.4	415.4
170	65	120	144.7	249.4
170	65	160	170.5	290.3
170	65	200	193.6	329.4
170	65	240	214.8	367.2
170	65	280	234.6	404.1
170	80	120	141.4	244
170	80	160	166.6	284.1
170	80	200	189.2	322.4
170	80	240	210	359.5
170	80	280	229.3	395.6
180	10	120	159	276
180	10	160	187.3	320.7
180	10	200	212.8	363.2
180	10	240	236.1	404.4
180	10	280	257.8	444.5
180	30	120	140.9	242.7
180	30	160	166.1	282.3
180	30	200	188.6	320
180	30	240	209.3	356.6
180	30	280	228.5	392.2
180	50	120	133.2	229.3
180	50	160	157	266.9
180	50	200	178.3	302.8
180	50	240	197.9	337.5
180	50	280	216.1	371.3

Kiln temperature (°F)	Initial wood temperature (°F)	Unit weight length (g/in.)	Heating time (min)	
			Predicted	99% upper confidence bound
180	65	120	129.5	222.9
180	65	160	152.6	259.5
180	65	200	173.3	294.5
180	65	240	192.3	328.3
180	65	280	209.9	361.3
180	80	120	126.5	218.1
180	80	160	149.1	254
180	80	200	169.4	288.2
180	80	240	187.9	321.4
180	80	280	205.2	353.7
190	10	120	144	249.7
190	10	160	169.6	290.1
190	10	200	192.7	328.6
190	10	240	213.8	365.8
190	10	280	233.4	402.1
190	30	120	127.6	219.6
190	30	160	150.4	255.4
190	30	200	170.8	289.6
190	30	240	189.5	322.7
190	30	280	206.9	354.9
190	50	120	120.6	207.5
190	50	160	142.2	241.5
190	50	200	161.5	274
190	50	240	179.2	305.4
190	50	280	195.7	336
190	65	120	117.2	201.8
190	65	160	138.1	234.9
190	65	200	156.9	266.5
190	65	240	174.1	297.1
190	65	280	190.1	327
190	80	120	114.6	197.4
190	80	160	135	229.8
190	80	200	153.4	260.8
190	80	240	170.2	290.9
190	80	280	185.8	320.1
200	10	120	131.6	228.2
200	10	160	155.1	265.2
200	10	200	176.2	300.4
200	10	240	195.5	334.4
200	10	280	213.5	367.6
200	30	120	116.7	200.8
200	30	160	137.5	233.5
200	30	200	156.2	264.7
200	30	240	173.3	295
200	30	280	189.2	324.5

Kiln temperature (°F)	Initial wood temperature (°F)	Unit weight length (g/in.)	Heating time (min)	
			Predicted	99% upper confidence bound
200	50	120	110.3	189.7
200	50	160	130	220.8
200	50	200	147.7	250.5
200	50	240	163.9	279.2
200	50	280	178.9	307.2
200	65	120	107.2	184.5
200	65	160	126.3	214.8
200	65	200	143.5	243.7
200	65	240	159.2	271.7
200	65	280	173.8	299
200	80	120	104.8	180.5
200	80	160	123.5	210.2
200	80	200	140.2	238.5
200	80	240	155.6	266
200	80	280	169.9	292.7
210	10	120	121.4	210.5
210	10	160	143.1	244.5
210	10	200	162.5	277
210	10	240	180.3	308.4
210	10	280	196.9	339
210	30	120	107.6	185.2
210	30	160	126.8	215.4
210	30	200	144.1	244.2
210	30	240	159.8	272.1
210	30	280	174.5	299.3
210	50	120	101.8	175
210	50	160	119.9	203.7
210	50	200	136.2	231.1
210	50	240	151.1	257.6
210	50	280	165	283.4
210	65	120	98.9	170.2
210	65	160	116.5	198.1
210	65	200	132.3	224.8
210	65	240	146.8	250.6
210	65	280	160.3	275.8
210	80	120	96.6	166.5
210	80	160	113.9	193.9
210	80	200	129.4	220
210	80	240	143.5	245.4
210	80	280	156.7	270
220	10	120	112.8	195.6
220	10	160	132.9	227.2
220	10	200	151	257.4
220	10	240	167.5	286.6
220	10	280	183	315

Kiln temperature (°F)	Initial wood temperature (°F)	Unit weight length (g/in.)	Heating time (min)	
			Predicted	99% upper confidence bound
220	30	120	100	172.1
220	30	160	117.8	200.2
220	30	200	133.8	227
220	30	240	148.5	252.9
220	30	280	162.2	278.2
220	50	120	94.5	162.7
220	50	160	111.4	189.3
220	50	200	126.5	214.8
220	50	240	140.4	239.4
220	50	280	153.3	263.4
220	65	120	91.9	158.2
220	65	160	108.3	184.2
220	65	200	123	209
220	65	240	136.4	233
220	65	280	149	256.4
220	80	120	89.8	154.8
220	80	160	105.8	180.2
220	80	200	120.2	204.5
220	80	240	133.4	228.1
220	80	280	145.6	251
230	10	120	105.5	182.9
230	10	160	124.3	212.5
230	10	200	141.2	240.8
230	10	240	156.7	268
230	10	280	171.1	294.6
230	30	120	93.5	161
230	30	160	110.2	187.3
230	30	200	125.2	212.3
230	30	240	138.9	236.6
230	30	280	151.6	260.2
230	50	120	88.4	152.2
230	50	160	104.2	177.1
230	50	200	118.3	200.9
230	50	240	131.3	224
230	50	280	143.4	246.5
230	65	120	85.9	148
230	65	160	101.2	172.3
230	65	200	115	195.5
230	65	240	127.6	218
230	65	280	139.3	239.9
230	80	120	84	144.8
230	80	160	98.9	168.6
230	80	200	112.4	191.4
230	80	240	124.7	213.4
230	80	280	136.2	234.9

Kiln temperature (°F)	Initial wood temperature (°F)	Unit weight length (g/in.)	Heating time (min)	
			Predicted	99% upper confidence bound
240	10	120	99.2	172.1
240	10	160	116.9	200
240	10	200	132.8	226.5
240	10	240	147.3	252.2
240	10	280	160.9	277.2
240	30	120	87.9	151.5
240	30	160	103.6	176.2
240	30	200	117.7	199.8
240	30	240	130.6	222.6
240	30	280	142.6	244.9
240	50	120	83.1	143.2
240	50	160	98	166.7
240	50	200	111.3	189.1
240	50	240	123.5	210.8
240	50	280	134.8	231.9
240	65	120	80.8	139.3
240	65	160	95.2	162.1
240	65	200	108.1	184
240	65	240	120	205.1
240	65	280	131	225.7
240	80	120	79	136.3
240	80	160	93	158.7
240	80	200	105.7	180.1
240	80	240	117.3	200.8
240	80	280	128	221
250	10	120	93.7	162.7
250	10	160	110.5	189.1
250	10	200	125.5	214.2
250	10	240	139.2	238.4
250	10	280	152	262.1
250	30	120	83.1	143.2
250	30	160	97.9	166.6
250	30	200	111.2	188.9
250	30	240	123.4	210.5
250	30	280	134.8	231.5
250	50	120	78.6	135.4
250	50	160	92.6	157.6
250	50	200	105.1	178.8
250	50	240	116.7	199.3
250	50	280	127.4	219.3
250	65	120	76.3	131.7
250	65	160	89.9	153.3
250	65	200	102.2	174
250	65	240	113.4	194
250	65	280	123.8	213.5

Kiln temperature (°F)	Initial wood temperature (°F)	Unit weight length (g/in.)	Heating time (min)	
			Predicted	99% upper confidence bound
250	80	120	74.6	128.9
250	80	160	87.9	150.1
250	80	200	99.9	170.3
250	80	240	110.8	189.9
250	80	280	121	209
260	10	120	89	154.5
260	10	160	104.8	179.5
260	10	200	119.1	203.4
260	10	240	132.1	226.4
260	10	280	144.3	248.9
260	30	120	78.9	136
260	30	160	92.9	158.2
260	30	200	105.6	179.4
260	30	240	117.1	199.9
260	30	280	127.9	219.9
260	50	120	74.6	128.6
260	50	160	87.9	149.7
260	50	200	99.8	169.8
260	50	240	110.7	189.3
260	50	280	120.9	208.3
260	65	120	72.4	125.1
260	65	160	85.4	145.6
260	65	200	97	165.3
260	65	240	107.6	184.3
260	65	280	117.5	202.8
260	80	120	70.8	122.4
260	80	160	83.4	142.6
260	80	200	94.8	161.8
260	80	240	105.2	180.4
260	80	280	114.8	198.5
270	10	120	84.8	147.3
270	10	160	99.9	171.2
270	10	200	113.5	193.9
270	10	240	125.9	215.9
270	10	280	137.5	237.3
270	30	120	75.1	129.7
270	30	160	88.5	150.9
270	30	200	100.6	171.1
270	30	240	111.6	190.6
270	30	280	121.9	209.7
270	50	120	71	122.7
270	50	160	83.7	142.8
270	50	200	95.1	162
270	50	240	105.5	180.5
270	50	280	115.2	198.6

Kiln temperature (°F)	Initial wood temperature (°F)	Unit weight length (g/in.)	Heating time (min)	
			Predicted	99% upper confidence bound
270	65	120	69	119.3
270	65	160	81.3	138.9
270	65	200	92.4	157.6
270	65	240	102.5	175.7
270	65	280	111.9	193.3
270	80	120	67.5	116.7
270	80	160	79.5	135.9
270	80	200	90.3	154.3
270	80	240	100.2	172
270	80	280	109.4	189.3

Appendix C—Equation for Calculating Upper Confidence Bound of Heating Time

The general formula for an upper $(1 - \alpha) \times 100\%$ confidence bound on a new observation (heating time) at predictor vector **x** is

$$\hat{\beta}^T \mathbf{x} + t_{\text{dof}}(1-\alpha) \times s \times \sqrt{1 + \mathbf{x}^T \left(X^T X\right)^{-1} \mathbf{x}} \tag{A–1}$$

where $t_{\text{dof}}(1 - \alpha)$ is the appropriate critical value from a Student's *t* distribution, *s* is the root mean residual sum of squares from the regression, and *X* is the design matrix for the regression.

For the multiple regression model,

$$\ln(t) = a_0 + a_1 x_1 + a_2 x_2 + a_3 x_3 \tag{A–2}$$

where

$$\mathbf{x} = \begin{pmatrix} 1 \\ x_1 \\ x_2 \\ x_3 \end{pmatrix} \tag{A–3}$$

$$x_1 = \left(1/T - 0.00493699\right)/0.00085843 \tag{A–4}$$

$$x_2 = \left(\ln T_0 - 3.50324182\right)/0.66897527 \tag{A–5}$$

$$x_3 = \left(\ln(W/l) - 5.23485105\right)/0.15586916 \tag{A–6}$$

The appropriate $t_{\text{dof}}(1 - \alpha)$ value for a 99% confidence bound is 2.3529 for heating time prediction to both 160 and 150 °F center temperature.

For the heating time prediction to a center temperature of 160 °F,

$$\begin{pmatrix} \alpha_0 \\ \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{pmatrix} = \begin{pmatrix} 5.23953 \\ 0.37915 \\ -0.07234 \\ 0.08647 \end{pmatrix} \tag{A–7}$$

$$s = 0.25714 \tag{A–8}$$

For heating time prediction to a center temperature of 150 °F,

$$\begin{pmatrix} \alpha_0 \\ \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{pmatrix} = \begin{pmatrix} 4.98222 \\ 0.29152 \\ -0.07342 \\ 0.08894 \end{pmatrix} \tag{A–9}$$

$$s = 0.22339 \tag{A–10}$$

For both the 160 and 150 °F predictions,

$$\left(X^T X\right)^{-1} = \begin{bmatrix} 6.849315\text{E}-03 & 2.918086\text{E}-08 & -3.283614\text{E}-09 & -1.342262\text{E}-10 \\ 2.918086\text{E}-08 & 6.984271\text{E}-03 & -7.859142\text{E}-04 & -3.212628\text{E}-05 \\ -3.283614\text{E}-09 & -7.859142\text{E}-04 & 7.082774\text{E}-03 & 8.306181\text{E}-04 \\ -1.342262\text{E}-10 & -3.212628\text{E}-05 & 8.306181\text{E}-04 & 6.994486\text{E}-03 \end{bmatrix} \tag{A–11}$$

Appendix D—Temperature Conversion Table (°F to °C)[a]

°F	°C	°F	°C	°F	°C	°F	°C	°F	°C
31	–1	71	22	111	44	151	66	191	88
32	0	72	22	112	44	152	67	192	89
33	1	73	23	113	45	153	67	193	89
34	1	74	23	114	46	154	68	194	90
35	2	75	24	115	46	155	68	195	91
36	2	76	24	116	47	156	69	196	91
37	3	77	25	117	47	157	69	197	92
38	3	78	26	118	48	158	70	198	92
39	4	79	26	119	48	159	71	199	93
40	4	80	27	120	49	**160**	**71**	200	93
41	5	81	27	121	49	161	72	201	94
42	6	82	28	122	50	162	72	202	94
43	6	83	28	123	51	163	73	203	95
44	7	84	29	124	51	164	73	204	96
45	7	85	29	125	52	165	74	205	96
46	8	86	30	126	52	166	74	206	97
47	8	87	31	127	53	167	75	207	97
48	9	88	31	128	53	168	76	208	98
49	9	89	32	129	54	169	76	209	98
50	10	90	32	130	54	170	77	210	99
51	11	91	33	131	55	171	77	211	99
52	11	92	33	132	56	172	78	212	100
53	12	93	34	**133**	**56**	173	78	213	101
54	12	94	34	134	57	174	79	214	101
55	13	95	35	135	57	175	79	215	102
56	13	96	36	136	58	176	80	216	102
57	14	97	36	137	58	177	81	217	103
58	14	98	37	138	59	178	81	218	103
59	15	99	37	139	59	179	82	219	104
60	16	100	38	140	60	180	82	220	104
61	16	101	38	141	61	181	83	221	105
62	17	102	39	142	61	182	83	222	106
63	17	103	39	143	62	183	84	223	106
64	18	104	40	144	62	184	84	224	107
65	18	105	41	145	63	185	85	225	107
66	19	106	41	146	63	186	86	226	108
67	19	107	42	147	64	187	86	227	108
68	20	108	42	148	64	188	87	228	109
69	21	109	43	149	65	189	87	229	109
70	21	110	43	150	66	190	88	230	110

[a]Conversion formula: $T_{°C} = (T_{°F} - 32)/1.8$