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Heat Treatment of Firewood for Emerald Ash Borer (*Agrilus planipennis* Fairmaire): Case Studies

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The movement of firewood within emerald ash borer (*Agrilus planipennis* Fairmaire) (EAB)-infested states and into adjoining areas has been a contributor to its spread throughout the United States and Canada. In an effort to prevent further human-aided spread of EAB and to facilitate interstate commerce, the USDA Animal and Plant Health Inspection Service and cooperating states in the EAB quarantine have established a heat treatment process to be used as a mitigating treatment to allow movement of firewood from EAB quarantine areas. Firewood producers have since been faced with challenges implementing heat treatment processes and meeting the treatment standard for firewood. In this article, we present four case studies, conducted at firewood heat treatment facilities, with the aim of addressing these challenges. Different heat treating strategies were used in each of these facilities to meet the particular needs of operation. A step-by-step operating procedure was developed for heat treatment operation and temperature monitoring of both kiln and firewood samples during the heating process.

Keywords: emerald ash borer, phytosanitary treatment, kiln, quarantine, operating procedure, temperature monitoring

Emerald ash borer (*Agrilus planipennis* Fairmaire) (EAB) has emerged as a devastating killer of ash (*Fraxinus* spp.) trees in the United States and Canada (Haack et al. 2002, US Department of Agriculture [USDA] Forest Service 2008, Klooster et al. 2014). As of May 2014, EAB-infested areas include 22 US states and 2 Canadian provinces (Michigan State University 2014, USDA Animal and Plant Health Inspection Service [APHIS] 2014). Extensive survey programs have been established to detect emerging populations in other areas. It is estimated that if EAB is not contained or eradicated, it will cost local government and homeowners $10.7 billion over the next decade for treatment or removal and replacement of ash trees on developed land within communities (Kovacs et al. 2010). This scenario would also result in extensive environmental damage and long-term changes in the North American forest structure (USDA Forest Service 2008).

The movement of firewood within EAB-infested states and into adjoining areas has been thought to be responsible for much of the spread of EAB throughout the United States and Canada (Michigan Department of National Resources 2004, Petrice and Haack 2006). Firewood producers typically harvest their wood within 100 miles of their processing facility; however, it is often sold to large retailers that commonly ship large volumes of packaged firewood hundreds of miles (Stiles 2004, Myers et al. 2009). To stop the further human-mediated spread of EAB from infested areas and to facilitate interstate commerce, the USDA APHIS Plant Protection and Quarantine (PPQ) has established a heat treatment standard as one option for allowing firewood to move across the quarantine boundary to noninfested areas (Code of Federal Regulations [CFR] 2011, USDA APHIS PPQ 2011). EAB is known to attack only ash trees (*Fraxinus* spp.) in North America; however, because of the difficulty of identifying spe-

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cies of cut wood by inspectors, quarantine regulations prohibit the movement of all hardwood firewood from known EAB-infested areas across quarantine boundaries, regardless of emerald ash borer status, or to adjacent noninfested areas unless proper heat treatment or another approved mitigating measure has been applied (Myers et al. 2009). The keys to the success of a heat treatment process are two-fold: increase the kiln/chamber temperature high enough to meet the EAB heat treatment standard at which the firewood core temperature reaches the kill temperature for an extended period of time; and monitor the core temperatures of the slowest heating pieces of firewood to ensure that the temperature-time requirement is met before the heat treating cycle is completed.

The current heat treatment schedule for EAB in firewood requires the core temperature to reach a minimum of 140° F for 60 minutes (Treatment Schedule T314-a; USDA APHIS PPQ 2011), a temperature-time combination proven effective against EAB larvae that resulted in a mortality of 100% within infested ash firewood (Myers et al. 2009). Before January 2011, a more stringent schedule (160° F for 75 minutes) was used (USDA APHIS PPQ 2010). The heat treatment standard for EAB exceeds the international heat treatment standard (ISPM 15) for solid wood packaging materials (133° F for 30 minutes) (Food and Agriculture Organization 2002) because of the higher thermal tolerance of EAB (McCullough et al. 2007, Nzokou et al. 2008, Myers et al. 2009).

The time required for the center of firewood to reach the kill temperature depends on many factors, including the type of energy source used to generate the heat, the medium used to transfer the heat (for example, wet or dry heat), and the species and physical properties (sizes, specific gravity, moisture content, and initial wood temperature) of the firewood being heat treated.

In the heat treatment operation, there is no practical reason to differentiate different hardwood species because the actual effect of species on heating times was not large (Simpson et al. 2005). In fact, the differences in heating times of different hardwood species are of a magnitude similar to the expected natural variability between individual pieces. In a previous project funded through the USDA Forest Service Wood Education and Resources Center (Princeton, WV), we examined the efficacy of different heat treatment options in meeting the heat treatment standard for EAB and developed empirical models for estimating heating times in various heating conditions (Wang et al. 2009, 2010). The project resulted in practical heat treating strategies for various firewood operations. The heating time tables that were developed have benefited firewood producers in planning and executing effective firewood heat treatment programs as required by the USDA phytosanitary regulations. An additional concern with heat treating of firewood is the practical challenge to implement federal regulations and meet current treatment standards. There is a lack of standard procedures in commercial heat treatment operations, and facility operators often do not have the necessary knowledge and expertise to properly run temperature measuring systems, conduct heat treatment operations with appropriate heat treating schedules, and monitor heat treatment processes to ensure that the treatment requirements are met.

The goal of this project was to transfer information on heat treatment technology to field operations through onsite demonstrations. The two specific objectives were to conduct demonstrations at four heat treatment facilities to train kiln operators and regulatory staff on the fundamentals of the heat treatment process and proper procedures for monitoring firewood core temperatures and to develop a generic operating procedure for firewood producers that incorporates the knowledge gained through the demonstration projects.

Heat Treatment Process

Kiln Certification

USDA APHIS regulations require that facilities conducting heat treatment of firewood for EAB must be inspected and certified by a PPQ official for initial qualification. The official certification test has three main components: calibrating the temperature sensors, thermal mapping (cold spot mapping), and conducting a certification test treatment (USDA APHIS PPQ 2012). Certified facilities are then issued a compliance agreement from USDA APHIS PPQ that permits the facility to move regulated firewood under the established provisions and conditions (7 CFR 301.53-6; CFR 2011).

Certified heat treatment facilities are also required to monitor the core temperatures of several firewood pieces during the heating process and maintain temperature records of each heat treatment run to verify that the conditions of the heat treatment schedule have been met. The firewood samples monitored are required to be placed in the coldest areas of the kiln/chamber that were determined by thermal mapping. The internal wood temperature should be collected at least once every 5 minutes and stored in a data file. The sensors used to monitor firewood temperatures need to be calibrated annually and

Management and Policy Implications

Because of the potential risk of emerald ash borer (*Agrilus planipennis* Fairmaire) (EAB) spread and establishment, the movement of firewood from areas currently known to be infested is restricted under state and federal quarantine regulations. Similarly, many states also prohibit the import of firewood, regardless of its origin, in an attempt to prevent the introduction of exotic forest pests. Heat treatment has been approved by state and federal agencies as a mitigating treatment for EAB to allow the movement of firewood from quarantined areas. The success of a heat treatment process depends on the heating capacity of the treatment facility and how well the system is operated. As part of any federal or state regulatory enforcement program, it is important to assess the heating capacity of all heat treating facilities, identify any deficiencies such as cold spots within the kiln, and determine requirements for the kiln to meet the EAB heat treatment standard. Properly monitoring the core temperatures of the firewood samples located in cold spots is a critical procedure in implementing an effective heat treatment operation. For kilns with limited heating capacity (such as those heated with hot water), a kiln temperature that is minimally 10° F above the required core wood temperature is necessary to achieve the treatment standard. The case studies reported here illustrate some potential errors that can compromise the effectiveness of the heat treating process when operating procedures are not carefully followed.

Table 1. Kiln facilities, temperature monitoring equipment, and heating performance of the heat treatment cases.

Case study	Kiln facility	Heating source	Temperature sensor	No. of sensors	Data logger	Firewood	Operation	Peak temperature (° F)	Heating time to 140° F (h)	Time of entire process (h)
1	Commercial dry kiln (Koetter Dry Kiln, Inc., Borden, IN)	Hot water	Thermocouple (type T)	4	4-channel portable data logger, (OM-SP1700-500, Omega Engineering, Inc., Stamford, CT)	Green	Heat treating and kiln drying	174–178	11–20	98–138
2	Commercial dry kiln (Northland Kilns, Inc., Bagley, MN) and custom-built dry kiln	Hot water	Thermocouple (type T)	8	8-channel thermocouple data logger, (USB TC-08, Pico Tech, Cambridgeshire, UK)	Green	Heat treating and kiln drying	165–170	16–74	120
3	Commercial dry kiln (Nova Dry Kiln, New Albany, IN)	Natural gas	Thermocouple (type T) and RTD probe	8	8-channel temperature data logger (OM-CP-OCTTEMP, Omega Engineering)	Seasoned	Heat treating only	205	4.4–5.2	5.4–6.2
4	Commercial dry kiln (Kiln-Direct, Burgaw, NC)	Hot water	Thermocouple (type T)	4	4-channel compact portable data logger (OM-SP1700-500, Omega Engineering, Inc.)	Seasoned	Heat treating only	165–172	16–22	17–23

read within ±0.9° F of the treatment temperature (USDA APHIS PPQ 2012).

Temperature Monitoring

Typically, commercial dry kilns and heating chambers designed for heat treatment are equipped with one or two temperature sensors or temperature gauges that display dry-bulb temperatures of the heating medium. Most kilns/chambers that are used to heat treat or dry firewood do not have a wet-bulb temperature sensor installed. (Note that wet-bulb temperature usage allows for greater control of kiln conditions necessary for drying lumber.) The dry-bulb temperature of the heating medium is normally referred to as the kiln or chamber temperature and is used for real-time monitoring of kiln conditions. In facilities without a computer monitoring or a control program, kiln temperature information is often not recorded. To meet the heat treatment monitoring requirement, a firewood producer may need to install a temperature recording device to obtain a record of temperature history of the kiln or individual chamber.

Monitoring the core temperature of firewood requires the use of temperature sensors that can be inserted into the core of the largest firewood pieces during a treatment run. The sensor should reach the center of the cross section if inserted from a side face or reach more than 4 in. deep if inserted from the end of the piece. The most commonly used temperature sensors for measuring wood core temperatures are a thermocouple and the resistance temperature detector (RTD). A thermocouple is a junction between two different metals that produces a voltage related to a temperature difference. Thermocouples are inexpensive, interchangeable, and available in different temperature ranges. Type T (copper-constantan) thermocouples are best suited for heat treatment applications because of their relatively smaller temperature range and standard limits of error lower than those of other types of thermocouples (Omega Engineering, Inc. 2011a). The RTD operates on the principle of changes in the electrical resistance of pure metals and is characterized by a linear positive change in resistance with temperature (Omega Engineering, Inc. 2011b). RTD sensors are generally more expensive than the alternatives because they contain platinum and are more difficult to manufacture.

The temperature monitoring system for a heat treatment operation can vary depending on the configuration and capacity of the heating chamber or kiln and the availability of the monitoring equipment. In general, a monitoring system for a heat treating operation should include multiple temperature sensors, a data acquisition and recording device, and a personal computer to operate the system. A variety of temperature data loggers are available for monitoring and recording temperature data for firewood heat treatment operations. In this project, we custom-built one temperature monitoring system for each participating producer based on the type and needs of each heat treatment facility. The goal was to select appropriate temperature equipment and build reliable, easy to operate, and cost-effective temperature measurement systems that typical firewood producers can afford. Table 1 lists the kiln facility and temperature monitoring equipment used in each case study. Detailed information of the monitoring systems is provided in the Case Studies section.

Operating Procedures

Based on previous experience gained through laboratory heat treatment and field kiln certification processes (Wang et al. 2009, 2010), we developed the following step-by-step procedures for conducting heat treatment runs and temperature monitoring of both the kiln chamber and firewood samples during the heating process. The operating procedure has been improved through the field demonstration cases in this study.

Step 1. Initiate the Temperature Monitoring System. The temperature monitoring system should be started before the heat treatment process begins. This is usually done by initiating the data logger before or immediately after loading of the kiln. However, we recommend that the data logger be initiated to collect data before loading of the firewood into the kiln to ensure that all of the temperature sensors function properly and that the temperature data are being recorded correctly.

Step 2. Select the Monitoring Samples (Largest Firewood Pieces). Carefully select the largest pieces of firewood for placement of temperature sensors. The size and forms of firewood vary and are difficult to quantify. APHIS regulations require that

the largest pieces of firewood be selected and used as temperature monitoring samples in each heat treatment run. If a firewood load includes both wet and dry pieces, wet pieces should be selected as monitoring samples because wet wood takes a longer time to reach the required core temperature than dry wood (Wang et al. 2009).

Step 3. Insert Temperature Sensors into the Firewood Samples. This is the key step in the temperature monitoring process and must be done carefully to avoid inaccurate temperature measurement. The proper way of installing temperature sensors is as follows:

1. Determine the center of the firewood. Mark the center of the cross section from the ends of the firewood and measure the depth to the center from a side surface.
2. Drill a small diameter hole into the center of the firewood to accommodate the temperature sensor. The diameter of the hole should be just large enough to allow the temperature sensor to slide into the wood, with a small amount of space to allow for swelling of the wood during heating. If a thermocouple wire is used to measure the core temperature of a firewood piece, drill a small hole into the center at the midsection of the firewood. If a long temperature probe is used to measure the core temperature, drill a small hole of at least 4 in. deep from the center of the end.
3. Insert a temperature sensor into the hole, ensuring that the tip of the sensor reaches the center of the firewood sample.
4. If a thermocouple wire is used, insert a toothpick into the hole beside the wire and cover the entrance to the hole with silicone to avoid heat transfer. If a solid probe is used, secure the probe in position by pressing a toothpick into the hole and then cover the entrance with silicon.

Step 4. Arrange the Samples. Place the firewood samples into the firewood bins, baskets, or bundles, ensuring that all of the firewood monitoring samples are buried deep within each bin, about halfway down. The bins containing monitoring samples should be placed in the cold areas in the kiln as determined by APHIS PPQ staff during the kiln certification process.

Step 5. Complete Kiln Loading. Once the test samples have been arranged, complete the loading and close the kiln door.

Step 6. Check the Temperature Monitoring System and Start Heating. We recommend that kiln operators record the initial kiln temperature, the initial firewood core temperatures, and the cycle starting time in a kiln operation journal.

Step 7. Monitor Temperatures. Periodically monitor the kiln temperatures (dry-bulb) and the core temperatures of the firewood samples.

Step 8. Complete the Heat Treatment Cycle. Determine the completion of the heat treatment cycle after verifying that the samples have met the conditions of the heat treatment schedule.

Case Studies

Commercial firewood operations vary considerably with regard to the types of kilns and other equipment they use to achieve the current heat treatment standard for EAB. These range from custom-built wood-fueled hot water systems and direct-fired units to commercially manufactured propane or natural gas-fueled direct-fired kilns designed to heat treat wood pallets as per ISPM 15 standards.

The choice of heat energy primarily depends on the heat treating method, energy resources available, and the cost of the energy. In this article, we present on-site heat treatment cases conducted at four firewood heat treating facilities that varied in size, types of kiln, and energy source (Table 1). Different heat treating strategies were used in these facilities to meet the particular needs of operation.

Case Study 1: Heat Treating and Kiln Drying Green Firewood with a Commercial Kiln Heated with Hot Water

Heat Treatment Facility. This facility includes a commercial dry kiln (Koetter Dry Kiln, Inc., Borden, IN), which measures 25 by 19.5 by 12 ft, and a hot water boiler (Mahoning Outdoor Furnace, Mahaffey, PA) with a heating capacity of 550,000 British thermal units (BTU) per hour. The kiln holds approximately 14 cords of firewood in a full load. The boiler is fueled manually with the facility's waste wood during kiln drying and heat treatment operations. The facility previously had difficulty raising the kiln temperature sufficiently in winter to levels required to meet the EAB heat treatment standard. Through participation in a previous field demonstration project (Wang et al. 2009), the owner made the following improvements on the kiln: added extra fin pipes to the heat exchanger inside the kiln to increase the heating area; added baffles to improve air circulation inside the kiln; and insulated the exposed hot water pipes between the hot water boiler and the kiln to reduce heat loss. After the kiln improvements, the kiln was able to reach 170° F during the winter months and 180° F in summer, which was proven sufficient to reach the previous heat treatment standard for EAB (160° F for 75 minutes).

Temperature Monitoring System. The temperature monitoring system we installed in this kiln consisted of four type T thermocouple wires, a four-channel temperature data logger (OM-SP1700-500 Compact Portable Data Logger; Omega Engineering, Inc., Stamford, CT), and a laptop computer. One thermocouple was mounted on the interior rear wall of the kiln to measure the temperature of return air (after circulating through firewood). Three thermocouples were used to measure the core temperatures of firewood samples placed in each of three baskets in the bottom layer of the back row. These locations were identified as the coldest spots in the dry kiln when it was thermal mapped by APHIS PPQ. At the time of the demonstration project, the heat treating facility did not have a control room on site to house a computer. Therefore, real-time monitoring was not available. Temperature data stored in the data loggers were downloaded and viewed after the completion of a heat treatment run by bringing a laptop to the site or taking the data logger back to the office. To allow the kiln operator to monitor the core temperatures of the firewood samples, we provided four additional thermocouple wires and a digital thermometer (HH82A; Omega Engineering, Inc.) as a secondary temperature monitoring system. Each of the three firewood samples had an additional thermocouple wire installed so that the core temperatures of the firewood could be monitored in real time using a digital thermometer during the heat treating process.

Heat Treatment Run. This facility has kiln dried fresh split firewood for interstate commerce for several years. Firewood loads were typically kiln dried weekly throughout the year. In this case, a dry heat schedule was best suited to the production needs of the facility by integrating a heat treatment procedure with a kiln drying pro-

cess. The heat treatment demonstration runs were performed to meet the heating standard set by USDA APHIS for EAB. After meeting the heating standard, firewood loads continued to kiln dry until the moisture content of the firewood fell below 20%.

Three heat treatment runs were conducted during the winter season using the established step-by-step operating procedure. In each treatment run, the kiln was fully loaded with fresh split firewood (a total of 27 4- by 4- by 8-ft baskets) (Figure 1). Baskets were arranged in three levels (bottom, middle, and upper), with nine baskets on each level. Firewood samples with thermocouples were placed in three baskets in the back row (identified as cold spots) of the lower level, one in the middle of each basket (Figures 2 and 3). The data logger was programmed to start temperature measurement before the heat treating started.

To achieve the highest possible kiln temperatures, the vents on the back wall of the kiln were closed to build heat mass during the heat treatment phase. The vents were then opened to release moisture after the heating standard was met to start drying the firewood. This procedure, combined with the infrastructure upgrades, proved effective in all three heat treatment runs.

In these three demonstration runs, peak kiln temperature reached 174–178° F during the heat treatment phase, and firewood samples reached the core temperatures of 140° F (current EAB heating standard) in 11–20 hours (Table 1). The large variation in heating time was associated with differences in initial wood temperature and ambient air temperature. Most importantly, it was affected by how frequently the water boiler was fueled. At the time of this project, a more stringent heat treatment schedule (160° F for 75 minutes) was used for EAB. Firewood samples reached the core temperatures of 160° F in 16.5–31.6 hours, and the entire kiln operation took 98–138 hours (4–6 days), a typical duration for kiln drying firewood at this facility. This observation indicates, at least in this example, that when a heat treatment process is integrated with kiln drying, the heating times to reach the required core temperatures are not critical as long as the heating standard is met before the completion of the kiln drying process.

Figure 1. Firewood baskets are placed into the kiln. The monitoring firewood samples were placed in the three baskets of the back row in the lower level. One instrumented piece was placed into each basket.

Figure 2. Thermocouple wires were inserted into the center of firewood samples at the midsection.

Case Study 2—Heat Treating and Kiln Drying Green Firewood with Custom Modified Kilns Heated with Hot Water

Heat Treatment Facility. This facility currently has two custom modified kilns for drying and heat treating firewood. At the time of this project, the facility had only Kiln No. 1 fully operational and had no temperature monitoring capability for either kiln. Because it was located outside of the EAB quarantine area, the facility was only required to heat treat firewood to the gypsy moth standard (133° F core temperature for 30 minutes) (Treatment Schedule T314-b; USDA APHIS PPQ 2011).

Kiln No. 1 is a modified Northland dry kiln (Northland Kilns, Inc., Bagley, MN) measuring 31 by 13 by 11 ft with a capacity of 5.2 cords of firewood in a full load. During kiln drying and heat treatment runs, a manually fed wood boiler (model CL 7260; Central Boiler, Greenbush, MN) provided 750,000 BTUs per hour to the kiln. The wood boiler was also capable of burning oil as an alternative. The heating coils and fans are located just beneath the ceiling along the

Figure 3. Firewood sample was placed in the center of a basket.

central line of the kiln. A tarp baffle is used to cover the top bins after loading and circulate hot air through the firewood bins during the heating process.

Kiln No. 2 was modified from a refrigerated cargo container. The kiln measures 8 by 9 by 48 ft and holds 6.5 cords of firewood in a full load. The heating coils and fans are installed at the upper corner through the length of the kiln. Initially, a custom-built wood furnace system provided hot air through ductwork to the kiln for heat. Later, the wood furnace was replaced with a manually fed wood boiler (model CL 40; Central Boiler), which provides 500,000 BTUs per hour. This newly upgraded kiln was not certified for heat treatment, and the air circulation condition was not known at the time of this project.

Our project at this facility was focused on installing a temperature monitoring system at Kiln No. 1 and demonstrating the proper heat treating and temperature monitoring process. At the owner's request, we expanded the monitoring system to include Kiln No. 2. Working with the APHIS PPQ staff, we conducted thermal mapping and kiln certification on Kiln No. 2 and installed six thermocouple wires at appropriate locations for monitoring internal firewood temperature.

Temperature Monitoring System. The temperature monitoring system was originally designed for the heat treatment process of Kiln No. 1 and included eight type T thermocouple wires, an 8-pair thermocouple extension cable, and an 8-channel data logger (USB TC-08 Thermocouple Data Logger; Pico Technology, Cambridgeshire, UK). Later, when the second kiln was added next to Kiln No. 1, we expanded the system by adding six thermocouple wires to Kiln No. 2. The heat treatment operation of Kiln No. 2 can be monitored by connecting these six sensors into the monitoring system. Because the data logger has only eight channels, only one kiln can be fully monitored at a time.

A thermal mapping test and heat treatment certification were performed by USDA APHIS PPQ staff on Kiln No. 1 before we installed the temperature monitoring system. Thermal mapping results indicated that the cold spots were located in the right side of the kiln near the two vents on the kiln wall. Therefore, we distributed four thermocouples in this cold area to measure the core temperatures of the firewood samples in four different bins. Four additional thermocouple wires were placed at different locations along the interior walls, with two on each side. These sensors were used to measure air temperature. In the demonstration runs, these four sensors were all used to measure air temperatures to check the heat distribution. In a normal operation, two sensors should be sufficient for monitoring the kiln temperature; additional sensors can be used as a backup in case any are damaged.

Heat Treatment Runs (Kiln No. 1). This facility produces split firewood and places firewood pieces into 3- by 3- by 3-ft steel wire bins before loading the kiln. A full load consisted of 44 bins arranged in three rows (9 bins on each side row and 4 bins on the center row) and stacked 2 bins high. The kiln operation of this facility included both heat treating and kiln drying. The firewood load was first heated to meet the heat treatment standard (heat treatment stage) and then kiln dried to ≤20% (kiln drying stage).

Two field heat treatment runs were conducted in Kiln No. 1 in the months of May and June. The whole process of heat treatment and kiln drying took 120 hours (5 days) for both runs (Table 1), which was a typical duration for drying green firewood at this facility. In the first kiln run, the kiln temperature was raised to 180° F for entering hot air and 170° F for return air (after circulating through firewood). The operation passed the heat treatment standard for gypsy moth (133° F for 30 minutes) in 72 hours and achieved the heat treatment standard for EAB (140° F for 60 minutes) in 74 hours. Although the facility was only required to meet the gypsy moth standard, this demonstration indicated that Kiln No. 1 also has the capability to meet the EAB heat treatment standard. In the second kiln run, the peak kiln temperature reached 170° F for the entering air and 165° F for return air. The operation passed the gypsy moth standard in 14 hours and passed the EAB standard in 16 hours. Examination of the temperature records indicated that the wood boiler was not sufficiently fueled during the heat treatment phase in the first kiln run, resulting a slower heating rate than that in the second kiln run.

Thermal Mapping of Kiln No. 2. USDA APHIS PPQ personnel conducted a certification test on Kiln No. 2 for intrastate movement of firewood. The purpose was to certify the kiln for heat treating firewood under the gypsy moth standard. HOBO U12 stainless steel temperature loggers (Onset Computer Corporation, Bourne, MA) were used to separately measure the air temperature and core temperature of firewood. A total of 26 loggers were placed into the kiln. Thirteen loggers were in firewood pieces located in the bottom layer of firewood bins and 13 adjacent to them to measure the air temperature. Temperature data were recorded every 5 minutes and downloaded from the loggers after the heat treatment.

Figure 4A shows the recorded temperatures from 13 data loggers that were used to

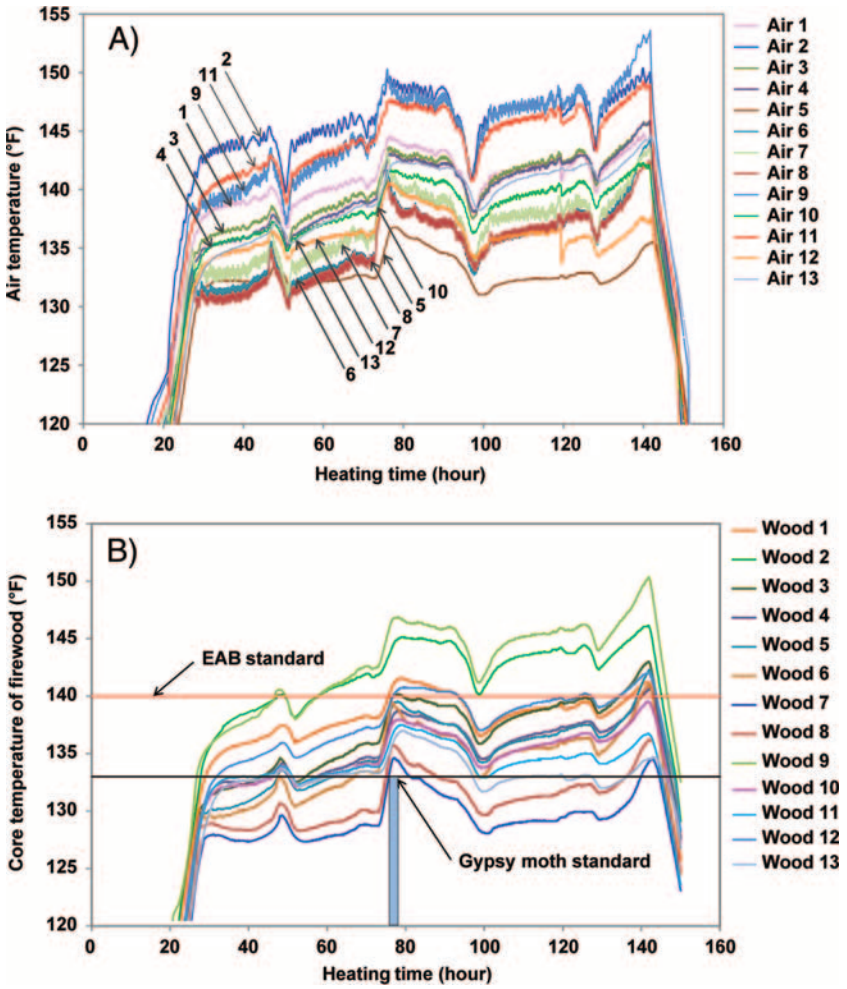

Figure 4. Temperature profiles recorded during thermal mapping in a custom-built kiln heated with hot water. (A) Air temperatures. (B) Core temperatures of the firewood samples.

map the air temperature distribution within the kiln. Figure 4B shows the recorded temperatures from 13 data loggers monitoring core temperatures of the firewood samples. All of the loggers measured temperatures above the gypsy moth standard. The thermal mapping results indicate that air was not well circulated in this modified kiln. The bottom bins that had the lowest air temperatures during the heating cycle were identified as cold spots. It was recommended that the temperature sensors be placed in these cold areas to monitor both kiln and firewood temperatures in future heat treatment operations.

Case Study 3—Heat Treating Seasoned Firewood with a Commercial Kiln Heated with Hot Water

Heat Treating Facility. This facility was previously certified to heat treat firewood for movement outside of EAB quarantine zone. The dry kiln (Nova Dry Kiln [formerly Koetter Dry Kiln], New Albany, IN) is approximately 18 by 18 by 10 ft with a capacity of 6.6 cords of firewood. A wood boiler was manually fed wood scraps to supply hot water for heating the dry kiln with a heating capacity of 275,000 BTUs per hour. This facility heat treated seasoned firewood for other producers. The firewood was transported to the facility in small bundles (0.75 ft^3) that were strapped with plastic wraps. The firewood bundles were then stacked on pallets and wrapped in plastic mesh (Figure 5). The firewood was heat treated in these stacked and palletized bundles. Because there were plenty of gaps within each bundle and between the bundles, the air flow through palletized bundles was not expected to be significantly different from that through firewood bins or baskets.

Temperature Monitoring System. To minimize the time required to place temperature monitoring probes, temperature sensors were inserted into the firewood pieces from the ends to avoid unwrapping the pallets and opening up the firewood bundles. This facility previously used a single thermocouple probe to monitor the core temperature of the firewood. Temperature data were recorded with a circular chart recorder (No. KT803; Dickson, Addison, IL). Hard copies of the circular charts were used to maintain treatment records for USDA APHIS. To improve the efficacy and ease of operation of the heat treating process, a new temperature monitoring system was installed to electronically record kiln and firewood temperatures.

The temperature monitoring system installed included three 4-in.-long type T thermocouple probes (for measuring firewood temperature), one type T thermocouple wire (for measuring kiln temperature), and a four-channel temperature data logger (OM-SP1700-500; Omega Engineering, Inc.). The Omega data logger was installed on the outside kiln wall in an adjacent storage room. The thermocouple probes were placed in three palletized firewood bundles on the back row, which was identified as the cold spot through thermal mapping and kiln certification.

Heat Treatment Runs. Three heat treatment runs were conducted in the month of September (run 1), October (run 2), and April (run 3). During the heat treatment operation, three of the five lower pallets closest to the rear wall had a sensor located in the center of the bundle to monitor firewood temperature. To install the temperature sensors, the mesh on the pallet was partially removed to access the bundles located in center of the bins. Three thermocouple probes were inserted into the firewood samples 4 in. deep from the end, and the gap was sealed using silicon sealant (Figure 5).

Temperature data from the Omega monitoring system showed that all three runs passed the firewood heat treatment requirement (140° F for 60 minutes) for EAB. The entire heat treatment process lasted 23, 17, and 20 hours, respectively. Insufficient fueling of the wood boiler during run 1 resulted in the system not maintaining kiln temperatures at night, prolonging the heat treatment cycle. All three bins met the temperature/time mark almost simultaneously, indicating good air movement through the palletized firewood.

Figure 5. A thermocouple probe was inserted into a firewood sample 4 in. deep from the end, and the gap was sealed using silicon sealant.

Case Study 4: Heat Treating Seasoned Firewood with a Direct-Fired Kiln Fueled with Natural Gas

Heat Treating Facility. This facility consists of a direct-fired dry kiln (Kiln-Direct, Burgaw, NC), a gas burner, and a small computer control room next to the kiln. The facility burns natural gas to provide heat source for heat treating both pallets and firewood. The kiln measures 48 by 15.5 by 11.5 ft and holds 11.5 cords of firewood when it is fully loaded. The normal heating capacity of the gas burner is 1,5000,000 BTUs per hour. This facility treats split hardwood firewood that has been air dried outdoors. Kiln drying is not required in the heat treating process. The firewood heat treatment operation uses the exhaust heat directly produced from the gas burner.

Temperature Monitoring System. The heat treatment kiln at this facility has an existing temperature monitoring system that was included with the dry kiln. This existing system used eight 2-in.-long RTD probes for temperature measurements: two for air temperatures located at the rear wall, about 4 ft aboveground and six for firewood core temperatures placed in the center of bins at the rear, middle, and front of the kiln. A computer is used to monitor the sensors in real time. The kiln was programmed to complete the heat treatment after the last of the six probes reached the EAB heat treating standard. In the past, the kiln operator had trouble with data recording. The owner agreed to install a second temperature monitoring system in the kiln as a backup system if the primary system was not operational. This situation provided us an opportunity to test our custom-built system and compare the use of two different temperature sensors (RTD versus thermocouple).

The new monitoring system consisted of eight type T thermocouple wires, an 8-channel temperature data logger (OM-CP-OCTTEMP; Omega Engineering, Inc.) and a desktop computer. The computer and the data logger were both housed in a small control room next to the kiln. Six thermocouples were used to measure the core temperatures of the firewood samples in the bottom six bins. These bins were located in the cold spot areas as identified through thermal mapping and kiln certification. Two more thermocouple wires were used to measure the kiln temperature, one for measuring the temperature of hot air that came out of the burner assembly and the other one for measuring the temperature of the return air.

Heat Treatment Runs. Three heat treatment runs were conducted in the months of September, October, and April. Split firewood was contained in 4- by 4- by 4-ft metal tube bins. These bins were loaded into the kiln by a forklift and arranged in three rows. Each row was 9 bins long and stacked 2 bins high for a total of 54 bins. Firewood bins were staggered to force heated air to make better contact with the firewood.

During the demonstration runs, both RTD probes and thermocouple wires were inserted into six selected firewood samples. The thermocouple wire was inserted into the center of each firewood sample at the midsection according to the established procedure. The 2-in.-long RTD probe was inserted into each firewood sample from the center of the end through a predrilled hole (1/4 in. diameter and 2 in. deep) and then plugged using a patch of duct seal putty (e.g., Rainbow Technology Corp., Pelham, AL). During the installation, we noticed that the putty patch attachment was not as secure as thermocouple wires. The installed RTD probes occasionally pulled out of the firewood during normal handling due to loose attachment. The other disadvantage of using this short RTD probe is that it can only go into the firewood 2 in. deep from the end. Therefore, the measured temperature may not reflect the true core temperature for that piece of firewood.

In this case, the temperatures measured by RTD probes and thermocouple wires were all monitored in real time and recorded through the desktop computer located in the control room. During a normal kiln operation, the Kiln-Direct program controlled the heating process. Data from the RTD probes indicated that the firewood samples reached 140° F in 3–3.75 hours. Data from the thermocouple wires showed that the firewood samples reached 140° F in 4.4–5.2 hours. There were obvious differences between the thermocouple readings and the RTD readings. Considering that both RTD probes and thermocouple wires had been calibrated before the run, the three possible causes of this difference were poor installation of RTD probes from the end of the firewood, possible falling out of the RTD probes from some firewood samples, and insufficient depth of RTD probes into the firewood samples. Thermocouple wires that were used to measure firewood core temperatures worked well during all three runs. No wire damage or dislodging from firewood was observed. If a temperature probe (whether RTD or thermocouple wires) falls out of the firewood, the operator can usually recognize this by looking at the temperature records. If it falls out during the kiln run, then there will be a temperature spike in the data that goes to the kiln temperature. Similarly, if the probe falls out during loading of the firewood, the temperature

from that probe will read the same as the kiln temperature throughout the run. A rapid rise in temperature can also be observed if it is not in a piece of firewood when the kiln starts up.

Key Considerations in Implementation

The success of a heat treatment process depends on the heating capacity of the system and how well the kiln is operated during the treatment period. Kiln certification is necessary for any heat treatment facility to test its heating capacity and ability to meet the heat treatment standards and to identify cold spots in the kiln so that those areas can be monitored when wood is being treated. In direct-fired kilns, the hot gases produced by burning gas, oil, or wood waste are discharged directly into the kiln through a mixing chamber. A facility equipped with a direct-fired kiln should be capable of obtaining kiln temperatures in the range of 180 to 200° F or above and meeting the current EAB heat treatment standard. In the case of a hot water-heated kiln facility, the heating times required to achieve the core temperature required to meet the heat treatment standard can vary with the initial wood temperature (or season of the operation) and how frequently the water boiler is fueled (Wang et al. 2009). If a kiln operation is intended for both heat treatment and kiln drying, the heating times are usually not critical as long as the heating standard is met before the kiln drying process is completed. For kilns with limited heating capacity, obtaining a kiln temperature at least 10° F above the required core wood temperature is necessary. To reach this minimum kiln temperature, it is recommended that the vents of the kiln be closed during the heat treatment phase to build heat mass. The vents can be opened to release moisture after the heating standard is met to start drying the firewood. Heat treating seasoned firewood takes much less time than heat treating and kiln drying fresh split firewood.

Monitoring the core temperatures of firewood pieces is critical in implementing an effective heat treatment operation. The temperature monitoring system for such an operation varies depending on the configuration and capacity of the heating chamber or kiln and the availability of the monitoring equipment. RTD was found to be not suited for measuring the core temperature of the firewood because it required drilling a relatively large hole (1/4 in.) either from the end or at the midsection of the firewood, and gaps between the probe and hole can be difficult to seal, thus causing heated air to enter into the hole and affect the readings of the RTD during the treatment. Another disadvantage is that RTD probes are fragile and can be damaged during a firewood handling process and replacing a new RTD probe is costly. Thermocouple wires have proven effective for measuring both kiln temperature and the core temperature of the firewood. Inserting a thermocouple into the center of a firewood piece is relatively easy, and it can be secured in position using a toothpick and silicon sealant. The typical cost for a basic monitoring system that includes thermocouple sensors and a data logger currently ranges from $1,000 to $2,000, depending on the number of data inputs required. A computer is essential for initiating the data logger, downloading temperature data, real time monitoring, and maintaining temperature data records.

Conclusions

In this study, we evaluated different types of temperature sensors/probes and data loggers for their applicability in the heat treating process and constructed easy-to-install temperature monitoring systems suitable for field heat treatment operations of different scales. Through four case studies conducted at the firewood heat treatment facilities, we demonstrated the effectiveness of a step-by-step operating procedure for conducting heat treatment runs and monitoring the temperatures of both the kiln chamber and firewood samples during the heat treatment process. Our case studies also revealed some potential errors when the operating procedure was not carefully followed. These include the following: not selecting the largest firewood pieces for temperature monitoring; inaccurate or inappropriate temperature sensor installation; and monitoring samples not allocated at the cold spots. Each of these issues could potentially compromise the effectiveness of the heat treating process and result in an underestimation of the time required to achieve the treatment requirements. Further research is needed to examine the possibility of developing generic thermal verification guidelines that are primarily based on kiln conditions (dry-bulb and wet-bulb temperatures of the heating medium), thus eliminating the need for physically monitoring the core temperatures of the firewood samples.

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